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VIDEO LASER BEAM RECORDER

AMPEX CORPORATION
REDWOOD CITY, CA 94063

APRIL 1977

TECHNICAL REPORT AFAL-TR-76-269
FINAL REPORT ~~APRIL 1976 - MARCH 1977~~

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AIR FORCE AVIONICS LABORATORY
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AIR FORCE SYSTEMS COMMAND
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This contract continues work accomplished on Contract F33615-73C-1213 and F33615-71-C-1371 to develop a high performance airborne dual channel 16 mm laser beam film recorder for television type sensors. Two channels of interlaced video pictures in 525 or 875 lines per frame format are recorded on film at 30 frames per second, with frames in Super 8mm format side by side on 2½ mil high resolution 16/mm film with variable density optical sound track for each channel.

The physical system, packaged in an airborne unit 12.75" x 32.75" x 29", consists of a helium-neon laser as a radiation source, acousto-optic modulators as electro-optic transducers, catadioptric flat field linear scan optics, ball bearing suspended 16-face rotating mirror polygon as horizontal scanner, galvanometer deflector as vertical scanner, and a rolling loop mechanism transport as film camera.

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The laser optics and control system attain 70% transfer efficiency at 16 MHz bandwidth. The rolling loop transport does not allow full realization of the performance of the laser optics and control system. Recommendations include sacrifice of frame height for film stability and de-interlace of video signals for film recording.

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FOREWORD

This is the final report on Contract F33615-73-C-1152, Air Force Project No. 7645, entitled "Video Laser Beam Recorder". This report covers the period from May 1973 to September 1976.

The cooperation of contract project engineer Stanley J. Rostocki of the Air Force Avionics Laboratory (AFAL/RSP) is gratefully acknowledged.

Primary contractor for this project is the Research Department of the Advanced Technology Division of Ampex Corporation, 401 Broadway, Redwood City, California 94063. The contractor's project number is EP-7197, and the report number is RR 76-10. In the course of the contract, the following Ampex personnel contributed to the technical effort:

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TABLE OF CONTENTS

SECTION		PAGE
I	OVERVIEW: PROGRAM SUMMARY	1
	1.1 Program Objectives	2
	1.2 System Approach	2
	1.2.1 Recorder System	3
	1.2.2 Film Transport	5
	1.2.3 Packaging and Structure	5
	1.3 Results	6
	1.3.1 Laser Recorder	6
	1.3.2 Film Transport	10
	1.3.3 Structure and Packaging	11
II	SYSTEM DEVELOPMENT	13
	2.1 History of Development	13
	2.2 System Designs	14
	2.2.1 Specification Summary	14
	2.2.2 System Concept	16
	2.2.3 Program Tasks	18
	2.2.3.1 Optical System	18
	2.2.3.2 Horizontal Scanner	22
	2.2.3.3 Vertical Scanner	22
	2.2.3.4 Polygon Scan Corrector and Intensity Control	22
	2.2.3.5 Beam Switcher	23
	2.2.3.6 System and Operating Control	23
	2.2.3.7 Film Transport	24
	2.2.3.8 Audio System	24

TABLE OF CONTENTS (Continued)

SECTION		PAGE
	2.2.3.9 Video System	24
	2.2.3.10 Package and Enclosure	25
	2.4 System Design Parameters	25
	2.4.1 Performance Parameters	25
	2.4.2 Design Parameters	26
III	SUBSYSTEM DESIGN	29
	3.1 Optical System	29
	3.1.1 System Design	29
	3.1.2 Scan Optics System	32
	3.1.3 Optical System	33
	3.1.3.1 Laser	33
	3.1.3.2 Intensity Control	36
	3.1.3.3 Beam Correction Lens	38
	3.1.3.4 Intensity Control	38
	3.1.3.5 Beam Splitter	39
	3.1.3.6 Acousto-optic modulators	39
	3.1.3.7 Beam Switchers	40
	3.1.3.8 Routing Optics	41
	3.1.3.9 Scan Optics	42
	3.1.3.10 Structure & Layout	44
	3.2 Horizontal Scanner	46
	3.2.1 Design Plan	46
	3.2.2 Scanner Polygon	48
	3.2.3 Bearings and Suspension	50
	3.2.4 Motor	51
	3.2.5 Mechanical Design	56
	3.2.6 Motor Driver	56
	3.2.7 Servo System	58
	3.2.8 System Performance	60

TABLE OF CONTENTS (Continued)

SECTION		PAGE
3.3	Vertical Scanner	61
3.3.1	Design Parameters	64
3.3.2	Mechanical Design	66
3.3.3	Driver & Timing	67
3.3.4	Performance	70
3.4	Video Processing System	70
3.4.1	Input Impedance Selector	72
3.4.2	Sync Separator	72
3.4.3	Timing Processor	74
3.4.4	Video Polarity Select	74
3.4.5	Automatic Gain Control	78
3.4.6	Gamma Select	81
3.4.7	Variable Bandwidth Filters	82
3.5	Acousto-optic Modulators	82
3.6	Film Transport Control	91
3.7	System Control	94
3.7.1	Basic Interlock Chains	94
3.7.1.1	Phase Locked Loop	98
3.7.1.2	Scanner Sync	98
3.7.1.3	Transport Sync	98
3.7.1.4	Film Brake	98
3.7.1.5	Test Mode	98
3.7.2	Remote Control	100
3.7.3	Internal Control	100
3.7.4	Input Panel	102
3.8	Acousto-optic Beam Switchers	102
3.9	Intensity Control	103
3.10	Film	108
3.11	Film Transport	108

TABLE OF CONTENTS (Cont)

SECTION			PAGE
		3.11.1 Transport Performance Criteria	110
		3.11.2 Transport Selection	112
		3.11.3 Basic Design	113
		3.11.4 Final Design	116
		3.11.5 Performance	118
	3.12	Audio Recording System	121
		3.12.1 Audio Amplifiers	121
		3.12.2 Recording Head	121
	3.13	Package	124
		3.13.1 Optical Deck	124
		3.13.2 Electronics and Power Supplies	124
		3.13.3 Auxiliaries	125
		3.13.4 Frame and Enclosure	125
4.0	SYSTEM PERFORMANCE		129
	4.1	Performance Summary, Statetment of Work Items	129
	4.2	Electronics/Optics System Performance	133
		4.2.1 Frequency Response	133
		4.2.2 Spatial Frequency Response	136
	4.3	Total System Performance	138
		4.3.1 Shading and Contrast	
		4.3.2 Line Positioning and Spacing	142
		4.3.3 Critique of Film Records	143
5.0	CONCLUSIONS AND RECOMMENDATIONS		149
	5.1	Conclusions	149
		5.1.1 Laser Raster Scanning	149
		5.1.2 Interlaced Video Format	149
		5.1.3 Film Transport	150
		5.1.4 Package	150

TABLE OF CONTENTS (Continued)

SECTION			PAGE
5.2	Recommendations		150
	5.2.1	Short Term Recommendations	150
	5.2.2	Long Term Recommendation	151
REFERENCES			153

SECTION I
OVERVIEW: PROGRAM SUMMARY

The Video Laser Beam Recorder program produced a flyable brassboard hardware solution to the wideband, high resolution cine film recorder requirement for dual channel video sensor reconnaissance surveillance. The Video Laser Beam Recorder provides direct photographic recording at high resolution of two wideband video sensor channels in super-8mm format on 16mm cine film.

The side by side format of the two images originating from, typically, Low Light Level TV and Forward Looking Infra Red video sensors provides direct real time scene comparison of two different spectral ranges when projected for assessment. A voice sound track associated with each video channel is provided to carry observer comment annotation of the scene.

The Video Laser Beam Recorder is the culmination of a developmental program initiated in 1969. The USAF foresaw the practicality of laser recorders to circumvent the shortcomings in bandwidth resolution, and complexity of equipment employed for generation of intelligence assessment cine films. Sensor technology had progressed to the point where, to take advantage of sensor capabilities, development of recording capabilities of comparable performance was required. The laser recorder, with its wide bandwidth and high resolution capability, directly produces projectable, first generation records on cine film at performance levels which fully utilize the most advanced sensor technology.

Preliminary analysis and investigation showed that the laser recorder could attain the bandwidths and resolutions required. However, analysis and laboratory experiements do not attempt to cope with operational requirements. The present program furthers the development of components and the system necessary to prove operational feasibility of the laser recorder in its designated operational missions.

1.1 Program Objective

The Video Laser Beam Recorder program has for its primary objective the achievement of greatly improved image recording capabilities over magnetic tape and kinescope recorders for TV-type sensors having bandwidth over 5 MHz. Equally important, the VLBR is required to be configured for airborne test and evaluation in modes approaching anticipated operational requirements.

The film record is a composition of recorded images from two TV-type sensors, the frames for which are placed side by side on a single, very high resolution 16mm cine film. Images are in super-8mm format with voice sound track for each channel of pictures.

The 525-line and 875-line pictures, produced with 2:1 interlace, are accurately registered and the raster uniformly generated to permit motion picture or single frame review without distractions due to flaws in placement or structure.

Faithful reproduction of the subject matter at high resolution is required, with electronic provision for expanding the video signal dynamic range to the full capacity of the film as a recording medium.

The film transport must operate at 30 frames per second, with the stability to permit attainment of full video to film information transfer. Frame to frame pulldown or blanking time should approach video vertical blanking period to minimize loss of frame information.

1.2 System Approach

Tradeoff studies of numerous viable combinations of available components were made, using as evaluation criteria availability, reliability, economy, and mission compatibility.

A two-channel wideband video system accepts signals from TV-type sensors, processes these for modulation of the acousto-optic modulators which produce an amplitude modulated laser beam carrying video information. The modulated light beams are scanned through lens systems to produce a raster, which is recorded on high resolution cine film as video pictures.

The physical system consists of a helium-neon laser as radiation source, acousto-optic modulators as electro-optic transducers, catadioptric flat field linear scan optics, ball-bearing suspended 16-face rotating mirror polygon as horizontal scanner, galvanometer deflector as vertical scanner, and a rolling-loop mechanism transport as film camera.

1.2.1 Recorder System

The recorder system was considered to be the primary area of concern in system development. To produce a superior image record on film, available films, laser, and support devices were optimally organized into a compact and durable recorder unit.

Initially, the film and the laser had to be optimized for the film exposure time, spectral sensitivity, and resolving power. Eastman Kodak type 3414 aerial reconnaissance film was determined to have the highest resolution potential of available films for exposure at the level required for use with reasonably compact, self-contained lasers. The laser selected as radiation source for the recorder is a 3 milliwatt helium-neon ruggedized laser, which is compact, self-contained, stable, and durable, with adequate radiant power for full range exposure after accounting for system losses.

The basic electrical to optical energy transducers, which cause electrical signals to modulate the laser beam at video frequency, are acousto-optic modulators. One for each data channel, the acousto-optic devices are applicable in the 16 MHz bandwidth range required for the system. Other factors, such as economy, insensitivity to polarization, and comparatively low power requirement made these the choice as electro-optical transducers.

Horizontal scanning of the modulated laser beams to effect line writing in the video picture raster is accomplished by a high speed rotating polygon mirror assembly. The scanner polygon is a 16-faced prismatic metal mirror driven by a brushless, servoed d-c motor. The basic brushless d-c, Hall element commutated drive motor was postulated and developed in previous Air Force contracts. To avoid the cumbersome compressed air supply for air bearing designs previously

considered, an elastomer supported ball bearing suspension is successfully employed in a scanner designed specifically for this application.

Vertical scanning of the modulated laser beam to effect video picture raster writing is accomplished with a low-inertia galvanometer-drive scan mirror. The basic design criteria and parameters were developed in previous Air Force contracts, but scan rate and beam size requirements necessitated design and construction of the electromechanical deflector to fit this application.

The scan optics system, which accepts the horizontally and vertically scanned collimated laser beams, focusses the beam on the film and causes the modulated, focussed spot to traverse the flat field film plane in a highly linear-time-position relationship. Catadioptric optics, shown to be feasible for the purpose in a previous Air Force contract are employed in conjunction with a pre-distorting system to effect precisely linear scan writing. Compact scan optics suitable for the recorder were designed for this specific requirement.

The video train electronics follow conventional commercial TV practice, except that bandwidth and fidelity requirements are well-beyond commercial standards. A complete design of video amplifiers and controls was necessitated to attain a high transfer function in the system. The video system also was required to accommodate and compensate for system peculiarities of the high-inertia mechanical elements working in cooperation with electronic elements. The video system encompasses compensations for non-linear response of modulators and film, as well as pre-distorters and limiters necessary for noise suppression and image enhancement.

The central system control is required to synchronize the electro-optical and electromechanical subsystem with the video signals. The system control, using the phase-locked loop circuit in the video train as the master system clock, provides timing, switching, and servo control to all operating subsystems. Operating control and interlocks are largely automatic, with only essential external controls and adjustments necessary for operation.

1.2.2 Film Transport

The primary requisites of a film camera, or transport, for small format, video raster recorded pictures are, first, stability of film relative to the recording beam scan, and secondly, minimal loss of frame content during raster writing. The 2:1 video interlace format requirement virtually precludes consideration of continuously moving film transports due to the difficulty of servoing relatively high inertia mechanical components at video rates to the extremely close position and velocity tolerances required. Of the intermittent motion cine film transports, the rolling-loop type most nearly fulfills pulldown requirements for a satisfactory kinescope-type transport. The rapid frame transfer rate or pulldown, with low accelerations on film and mechanical parts gave indication that the rolling loop transport was the most likely to meet the criteria for a satisfactory kinescope camera. Encouraging progress with development and use of the rolling-loop transport as a kinescope camera transport in an Air Force contract nearing completion at the time of inception of this program further appeared to confirm the choice as a viable system element.

1.2.3 Packaging and Structure

The basic packaging design problem involved configuration of the structure containing the optical train to compactly accommodate the dual 100-inch long optical path in a stable structure, while maintaining accessibility to the system elements. All optical parts are mounted to a stable and structurally rigid optical deck to maintain alignment integrity in critical areas of the system. The optical deck is isolated from the enclosure frame structure by soft vibration mounts to minimize transfer of strains and vibrations from frame to the optical deck. The film transport and film magazine are rigidly mounted to the optical deck, also, to preclude relative motion during recording.

The optical deck and film transport are surrounded by the video and control electronics in a chassis and rack. Various other support function equipment is placed around the deck to attain the most compact package under the circumstances.

In the scale of importance of design objectives, the package size and weight were considered least important, where comprises regarding performance and design effort were concerned. It was considered that proof of feasibility of the system as a high performance recorder was paramount, while physical size and weight constraints were secondary, as long as equipment was portable and flyable within the spirit of the objectives.

1.3 Results

The results of the program briefly stated, are that the laser recorder, or more correctly, the laser optics and control system, realizes the potential specified or expected of it. The rolling loop film transport, while performing adequately in many respects, does not allow full realization of the performance of the laser optics and control system. The package size and weight, although exceeding the design goal of three cubic feet and 120 lbs. by a considerable margin, can be reduced to within these figures by a production design effort.

The laser recording system is a high performance, flyable "brassboard" equipment, ready for field and limited operational test. The finished package is shown in Figure 1.

1.3.1 Laser Recorder

The laser recorder system is considered to be the major task of the program. The recorder section is defined, for purposes of this report, as that part of the system based on the optical deck, up to the film transport interface. The recorder section also includes support electronics involved in carrying data and producing synchronizing signals to operate the optical deck components. Proper performance of this group was the primary objective of the program; it is in this group that laser recorder feasibility had to be clearly established. The recorder section is a combination of active and passive optical, electro-optical and electromechanical components. Actuation of each active element must be synchronized within nanoseconds, while regulating response precisely.

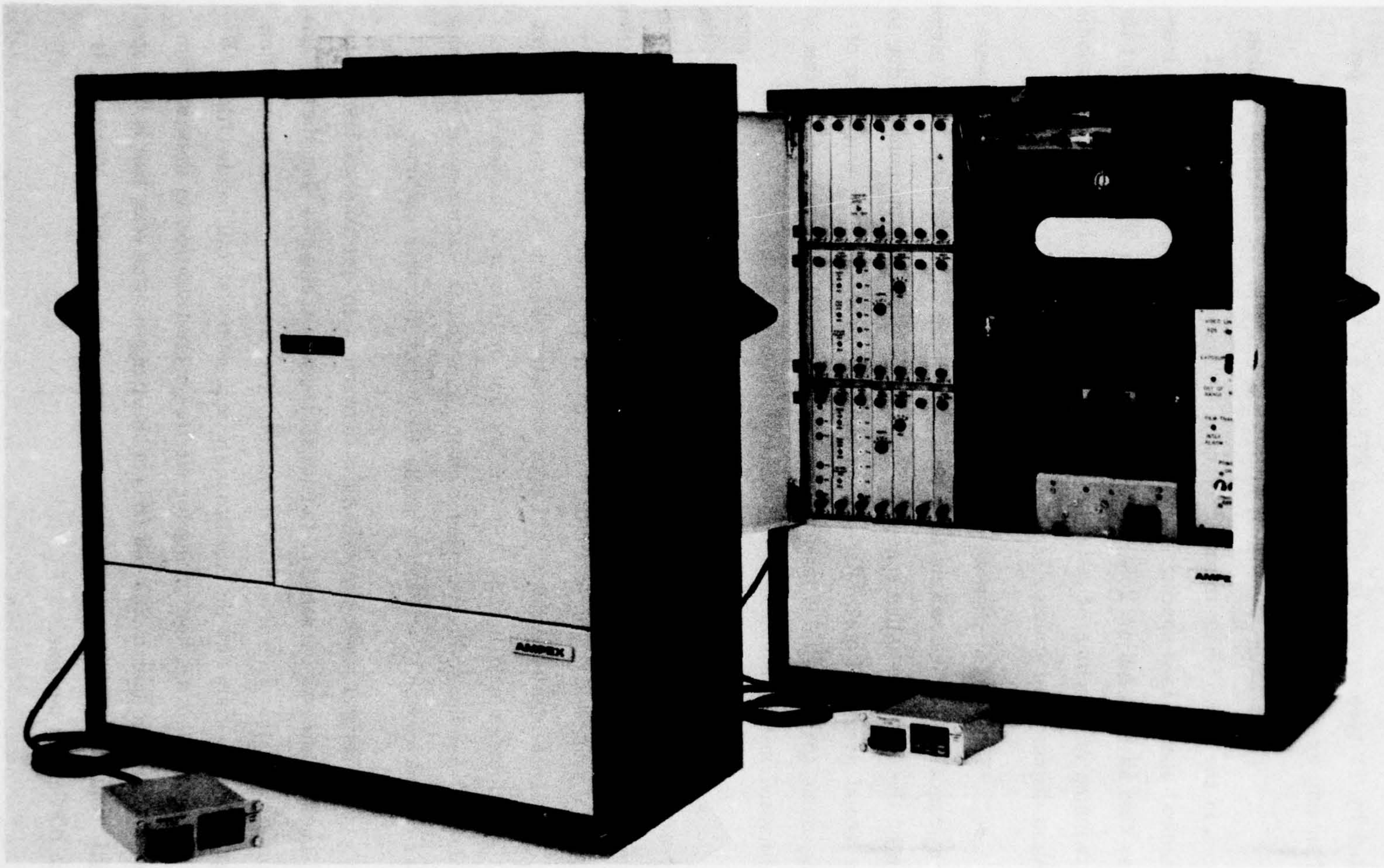


Figure 1 Video Laser Beam Recorder

The system is required to faithfully reproduce the pictorial scene generated by TV-type sensors in 525 and 875-line TV formats at 30 frames per second in side by side super-8mm format. The format is shown in Figure 2.

The 875-line TV format raster, laid down in 2:1 interlace, requires that lines in the 0.166" high frame (4.21 mm) be spaced 205 microinches (5.2 micrometers) apart. Line spacing in each field is 410 μinches; fields must be interlaced so that all lines fall on 205 μinch centers (5.2μ) within 58μ inches (1.5μ) to avoid twinning or bunching of raster line. Twinning and bunching, or any periodic or random displacement causes distortion of scene density and position.

The vertical scanner, or galvanometer driven mirror system, repeats position from field to field within 0.04 line space in an 875-line frame. The major portion of the 0.25 line-to-line space rms error (51 μin. or 1.3μm) noted is due to a 10 arc second pyramidal horizontal scanner polygon error. Further correction of the line-to-line spacing error is feasible, but not accomplished in this effort; this is fully discussed in the subsystem design section following.

Line start error, or the horizontal scan position error, determines the fidelity of placement of vertical lines in the frame. The recorded line-to-line placement error of 0.25 scan spot diameter (59 μin. or 1.5 μm) is due to a combination of horizontal scanner polygon azimuthal error (6 arc sec. max.) and scanner servo error. Polygon azimuthal error is 0.17 spot diameter (40 μin. or 1.0 μm); bearing runout contributes approximately half this amount or 0.08 spot diameter, for a total of 0.25 spot line-to-line placement error. Line-to-line scanner rotational error is under one nanosecond per line, or under 0.03 spot diameter per line.

Vertical resolution fidelity is determined by precision of line-to-line raster spacing; horizontal resolution fidelity is basically limited by line start or line position error in the electromechanical system. The transfer of video information through the video train and the acousto-optic modulators at full bandwidth is 16 MHz, flat within 0.5 dB, accounting for electronic pre-distortion to linearize film response. The scan spot is 235 μin (6 μm) in diameter; one scan line is 950 spots in length. At the maximum bandwidth, optical resolution, transfer efficiency, is 70% at 500 cycles per line.

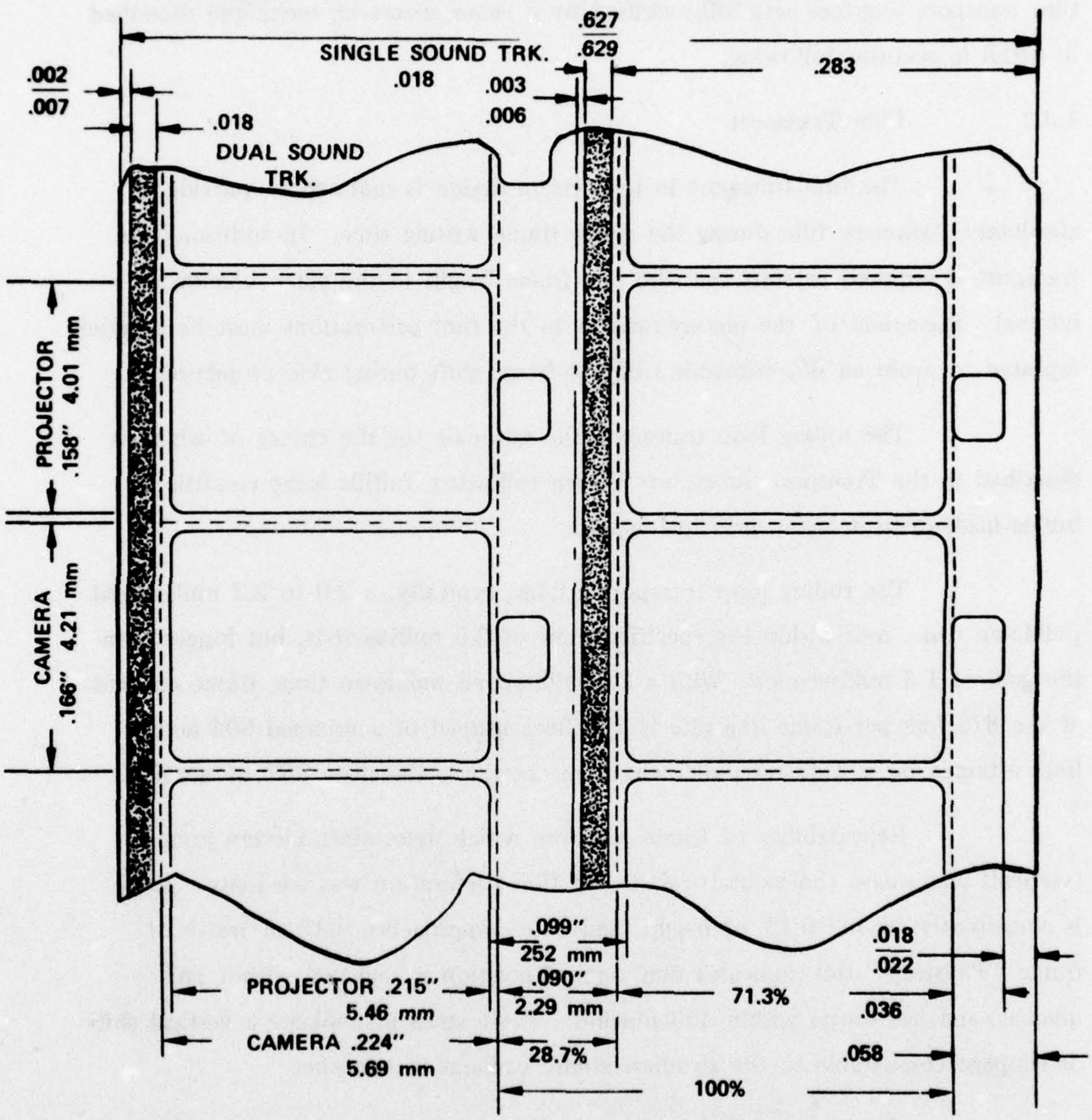


Figure 2 Format, Dual Super 8 mm

Due to the small instabilities of film encountered in the rolling loop film transport, discussed in detail in section following, full transfer of optical information to film was not attained. However, performance of the recorder up to the film transport interface was fully verified by a video cross-scan technique described in detail in sections following.

1.3.2 Film Transport

The film transport in the system design is required to provide an absolutely stationary film during the active frame writing time. In addition, the transport is required to shift the film one frame height in the video blanking interval. Placement of the picture relative to the film perforations must be precisely repeated to avoid an objectionable frame-to-frame shift during cine projection.

The rolling loop transport, the rationale for the choice of which is described in the Transport Subsystem Design following, fulfills some conditions, but is inadequate in many principal aspects.

The rolling loop transport attains, typically, a 2.0 to 2.2 millisecond pulldown time, well within the specified limit of 2.5 milliseconds, but longer than the goal of 1.3 milliseconds. With a 2.0 millisecond pulldown time, frame content at the 875 line per frame line rate is 778 lines instead of a nominal 804 active lines attained by a 1.33 ms pulldown. Frame height is therefore 96% of nominal.

Repeatability of frame position, which determines picture jump (vertical) and weave (horizontal) relative to film perforation was adequate. Jump is consistently around 0.1% of height, and weave approaches 0.2% of width of frame. Physically, this indicates that vertical position is repeated within 167 μinches, and horizontal within 450 μinches. These statistics indicate a vertical shift or slippage comparable to the steadiest studio cameras in existence.

However, stability, or movement, of film during recording remains a serious problem. Properly adjusted, film movement during recording can be as low as 100 to 200 microinches, with excellent possibility of motion compensation within the vertical scan electronics. Predominantly, however, the film shifts as much as 0.002 inch (2000 μin) and typically 0.001" in the first 16% of the frame writing period, causing vertical resolution degeneration in the top third of each frame.

It is possible by meticulous adjustment to reduce film motion to 100 μinches, but even this movement, equivalent to one-half of the nominal line spacing in the 875 line format, causes noticeable vertical image degeneration in the upper third of a frame. This displacement was detected early in the program, and diagnosed as motion which could be compensated by change in vertical scanner velocity and position. However, the more typical gross film shifts (0.001") appeared to make the electronic vernier adjustment an ineffectual plan which has not been implemented.

A full discussion of the film transport development is included in the Transport Subsystem section following.

Major conclusions reached during the program as regards transports are:

1) No presently available transport will provide the stability required to realize full information transfer to film in an interlaced video system. It is concluded that, for full image transfer from video to film, a de-interlaced raster is essential. Small movements of film which obliterate a high resolution raster become minor distortions in a non-interlaced raster.

2) The rolling loop transport holds greatest attraction for short pulldown times, but fundamental characteristics in other aspects of transport relegate the rolling loop mechanisms to an inferior status as ultra stable film transport.

3) Since the laser recorder-transport interface is clean and comparatively unrestricted, other, possibly more suitable, transports can be adapted to the recorder optical deck.

1.3.3 Structure and Packaging

As indicated in the system approach discussion, with the exception of the optical deck assembly, packaging received the lowest priority in design tradeoff decisions.

The optical deck mounts all the optical, electro-optical, electromechanical, and mechanical devices acting on the optical train. The dual 100 inch optical paths and the modifying elements distributed along the paths are contained in a light weight, rigid structure 1963 cu. in. in volume, or 0.98 cu. ft.

The film transport which, with film magazine attached, mounts rigidly to the optical deck. Transport and magazine volume are 564 cu. in. or 0.33 cu. ft. Total volume occupied by the optical deck with transport and magazine mounted is 1.31 cu. ft.

The total system package volume is 7.0 cu. ft. The 5.69 cu. ft. of space around the optical deck and camera are occupied by frame, enclosure, electronic chasses, power supplies, fans, power transformer, and power amplifiers. As a result of design and construction effort tradeoffs, the electronics chasses are compact by commercial solid-state electronics standards, but bulky by avionics standards. Power supplies and power amplifiers are compact commercially available units, considerably larger than similarly rated avionic equipage. Aerospace and avionic design practices and procedures in a product engineering effort can undoubtedly reduce package size to the specified 3.0 cu. ft. volume. However, the funds required to product engineer the package to the 3.0 cu. ft. size were disproportionate when the effort required in more basic development factors affecting system feasibility and performance was considered.

The optical deck is isolated from the enclosure structure and frame by soft vibration mounts to preclude distortion of the optical path by strains on the external package structure. It is recommended that the enclosure be mounted on vibration isolators in the aircraft to further isolate the system from low order shocks and vibration.

Total weight of the system is 226 lb.

Power required is 6.4 amp. at 117v, 400 Hz, single phase.

SECTION II
SYSTEM DEVELOPMENT

2.1 History of Development

The Video Laser Beam Recorder program was initiated in November 1969 by the Air Force as a study to investigate the feasibility of laser recorders as airborne wideband cine recorders. Subsequent contracts advanced the investigation and provided basic system component development toward an operating recorder system.

The effort of Contract No. F33615-70-C-1213 is reported in document AFAL-TR-70-23 (Ref. 1). The study investigated system requirements of direct video recording on photographic film, utilizing a laser as radiation source. The study further investigated system components required for wideband, interlaced video recording on film. A breadboard model of low inertia galvanometer necessary as a vertical scanner, was constructed. The preliminary design for a catadioptric, flat field scan optic system and a high-speed rotating polygon horizontal scanner were proposed.

The effort of Contract F33615-71-C-1371, reported in AFAL-TR-72-109, (Ref. 2) continued the study of critical components. An advanced galvanometer deflector for vertical scanning and a high-speed, air bearing rotating polygon assembly for horizontal scanning were constructed. These elements were combined with a complex catadioptric scan optic breadboard system to record video rasters on stationary film. The problems of video recording on silver halide film were sufficiently identified to permit generation of a specification for a flyable, high performance laser recorder for television-type sensors.

The effort recently completed has produced a flyable "brassboard" which produces high resolution recordings on photographic film.

2.2 System Designs

2.2.1 Specification Summary

The previous efforts in defining the requirements for a practical airborne laser recorder produced the specification and statement of work which defines a total Video Laser Beam Recorder System. The Statement of Work of Contract No. F33615-73-C-1152 defines the general objectives, basic approach, and performance requirements for such a recorder. The magnitude of the task of developing, designing, and constructing a working system for the precision required is indicated by the following specification summary.

Hardware: Contractor will produce a flyable engineering brassboard.

Performance Evaluation: By laboratory tests and flight tests. Preliminary evaluation on optical/electronic performance; final, on total performance on film.

Basic Objective: Produce a dual super-8 mm laser beam recorder for TV-type sensors, with audio track; 30-frame per second cine film recording.

Power: 400 watts max., Mil-Std-704, Cat. C power.

Warm-Up Time: Five minutes.

Video Input: Two separate and simultaneous NTSC or EIA TV-type signals to RS-343,330, & 170 standards. Line rates 525 and 875 per frame, Composite or separate sync, 1.0 to 2.5 volts.

Input Impedance: Selectable 50, 75, 92 ohm.

Audio Input: 0 - 5V into 5000 ohms. AGC required.

Controls: Configuration and operation modes specified, includes "Lamp Test", film frame counter, film fault indicator, and "Auto Run" mode to record 1802 frames automatically on signal.

Film: 16 mm film perforated dual super-8 mm, 2R1667 (1-3) per ANSI PH 22.150; also super-8 mm, 1R1667 per ANSI PH22.149 as a goal.

Format: Two super-8mm frames, ANSI PH22.157 side by side on 16 mm film.

Frame Rate: 30 frames per second, 60 fields per second.

Audio Track: ANSI standards, magnetic or optical.

Film Supply: 220,000 frames per track, Kodak 1414 or 130,000 frames, Kodak 3414.

Reliability: MTBF 200 hours; MTTR 0.5 Hr.

Maintainability: Mil-Std-470

Packaging: Size 8 x 18 x 36 inches max.

Transport Malfunction: Sensor required to detect transport film break.

Power Supplies: Self-contained power conversion for all functions from input A/C.

Electro-Optical Components: Ruggedized laser, wavelength optional; Film bias control and intensity control; scanning by four beams, modulated in pairs; modulators for intensity modulation of beams; gamma control, four steps 1.0 to 1.5; picture polarity reversal capability; line scan by single scanner; catadioptic relay system plus scan angle demagnifying lens; distortion mask for line straightening; flat field final linear scan lens; electromechanical deflector vertical scanner.

Film Transport: Pin registered, intermittent motion.

Film Transport Pulldown: Under 2.5 milliseconds, 1.16 ms goal.

Transport Test Gate: Focus device required to evaluate spot and scan.

System Frequency Response: 16 MHz ±0.5 dB.

Variable Bandwidth Select: Video bandwidth limiting filters, selectable 2, 4, 8, 12 MHz.

Spatial Frequency Response: 50% MTF at 500 sinusoidal cycles per line in the scan direction. Vertical direction 785 lines @ 875 line rate and 480 lines @ 525 line rate at 50% MTF with square wave impulses. Response flat within 5% center to edge.

Contrast Ratio: 200:1

Shading: Large area ±2%, small area ± .005 density units.

Synchronization: Input maximum jitter ± 100 nanoseconds.

Scan Position Accuracy: In Line ± 4 spot diameters.

Line-to-Line Deviation: 0.5 spot diameter.

Maximum Deviation: 1.0 spot diameter in any frame.

Line Positioning & Spacing: No bunching, spreading, or grouping.

Gray Scale: 15 step gray scale w/.15 density units steps on film.

Raster: Within ±0.1 mm per ANSIPH 22.157, orthogonal to $1/3^{o}$.

Steadiness: Jump and weave under .001".

Raster Linearity: Under 1%, center to edge.

Raster Line Control: Standard field, less 10 lines permissible.

Spot Geometry Control: Variable vertical spot dimension control.

Contract Enhancement: AGC, expand, compress, stretch video signals.

Film Load Time: Under 1 minute.

Setup Time: One hour per week.

Operating Temperature: $10^{o}C$ to $60^{o}C$.

Altitude: 0 - 10,000 ft.; 25,000 ft. design goal.

Size: Under 3.0 cubic feet.

Weight: Under 120 lb.

2.2.2 System Concept

The statement of work in effect delineates the concept of the Video Laser Beam Recorder. The major system elements are:

Recording Film: Kodak 3414 or 1414, 16 mm Aerial Reconnaisance Film, perforated 1 - 3 for dual channel Super-8 mm recording.

Laser: Ruggedized helium-neon laser (632.8 nm).

Modulators: Acousto-optic, 20 MHz bandwidth.

Scan Optics: Catadioptric relay, with scan linearized and flat field final focus.

Horizontal (line) Scanner: 16-faced prismatic polygon suspended on ballbearings, driven by a servo-controlled brushless d.c. motor.

Vertical Scanner: Electromechanical (galvanometer) deflator.

Beam Switchers: Acousto-optic deflectors.

Film Transport: Rolling loop transport with 1,000 foot film magazine and two channel audio record heads.

The system block diagram of Figure 3 shows the relationship of the major elements and the supporting video and control system components.

To process the electrical video signals, in each channel, video system functions were separated into functional chasses: Input impedance select (50, 75, 92 ohm), video sync separator, video timing processor polarity select and video AGC, AGC control, gamma select, bandwidth select, modulator pre-emphasis, modulator oscillator and mixer, and modulator driver amplifier. The processed video modulates the Bragg cell of the acousto-optic modulator, which intensity modulates the laser beam at the frequency of, and proportional to, the video signal amplitude.

The optical train consists of the laser, acousto-optic intensity control, intensity control detector, beam splitter, acousto-optic modulator, two acousto-optic beam switches, horizontal scanner, scan optics, electromechanical vertical deflector, and final focus lens.

System logic and control, synchronized to video by various multiples of the video horizontal and vertical scan rate by clock pulses generated by the video timing processor, consists of a polygon correction and intensity control, scanner servo, acousto-optic carrier frequency generator and beam switcher control, transport servo, motor power amplifiers, system operating logic and control, and remote control.

The film transport, a separable assembly, operates under control of the system logic and control network.

Development, design, and performance of each subsystem and major components are covered in detail in the report following.

2.2.3 Program Tasks

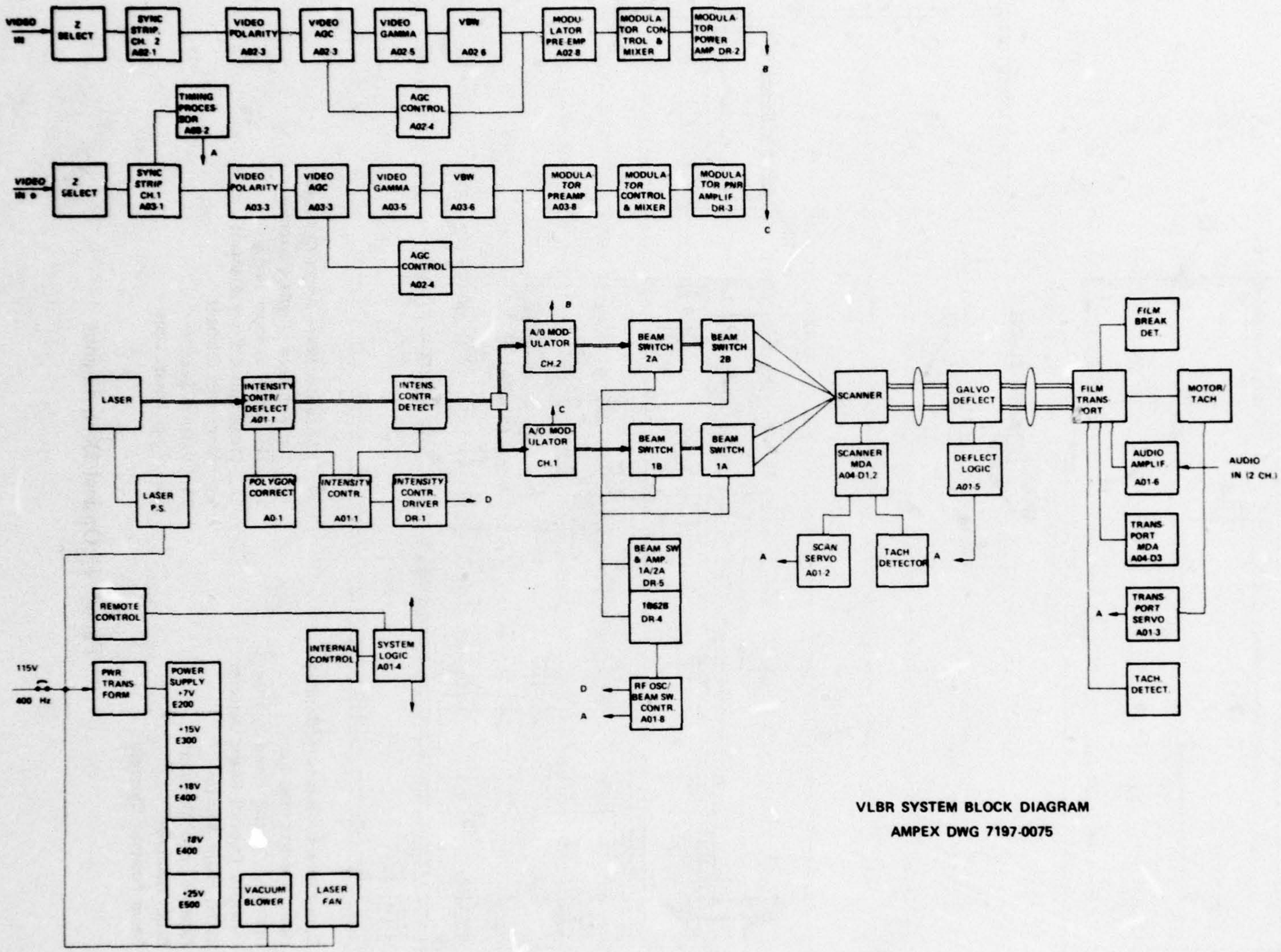
The considerable progress made previously in the development of the vertical scanner, horizontal scanner, and the design criteria established for the optical system provided an excellent base from which to develop a total Video Laser Beam Recorder system.

However, development and construction of the recorder system required, in addition to system analysis and engineering, the design and integration of ten major subsystems. The tasks on subsystems ranged from total development to straightforward engineering. While design criteria and parameters developed on preceding studies were invaluable, all subsystems in the VLBR are to a large degree unique in performance and configuration. To attain the objectives for a dual channel small format compact video LBR, no previously constructed hardware was applicable.

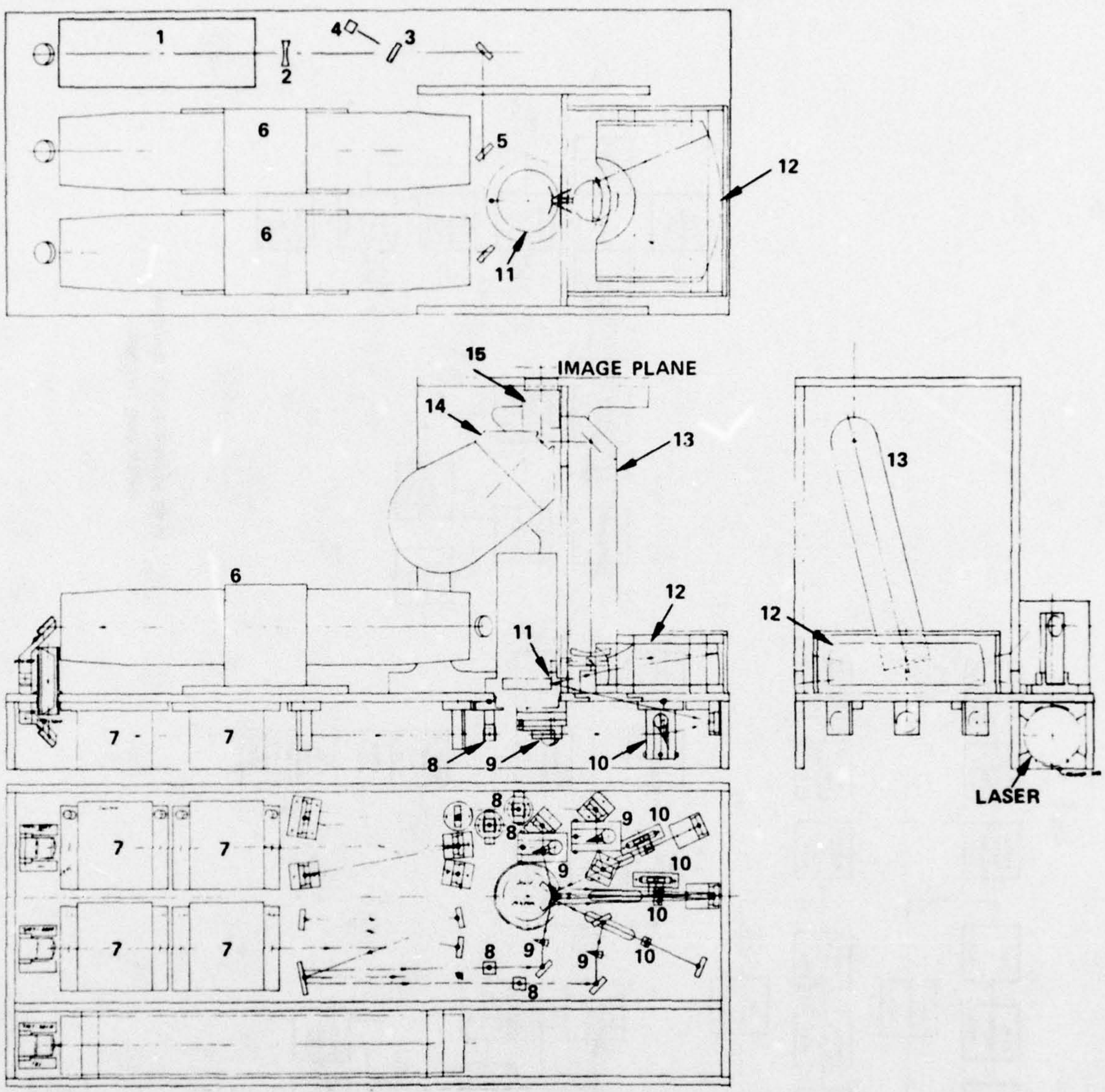
2.2.3.1 Optical System

Once the system analysis had established component performance criteria, the dual, 100 inch optical paths required to include all components needed were examined to find a suitable arrangement within program objectives. Certain components, such as modulators, laser, vertical deflector, and, to some extent, the horizontal scanner had established minimum envelopes and orientation to the optical path which severely restricted the packaging options. Others, suoh as the scan optics and routing optics, were flexible in arrangement but inflexible in spacing.

The most compact configuration which provides full mounting for all elements, with a structure that provides system integrity, and component accessibility, is shown in Figure 4. A perspective view of the optical deck components and optical path is shown in Figure 5.



System 3 System Block Diagram



1. Scan Corrector-Intensity Control
2. Beam Conditioning Lens
3. Intensity Control Beam Splitter
4. Intensity Control Beam Detector
5. 50-50 Beam Splitter
6. Acousto-optic Modulator
7. Beam Switcher
8. Beam Position Corrector
9. Horizontal Beam Angle Corrector
10. Vertical Beam Angle Corrector
11. Horizontal Scanner Polygon
12. Catadioptric Relay Element
13. Linearizer Element
14. Vertical Scanner
15. Final Focus Lens

Figure 4 Optical Deck Layout

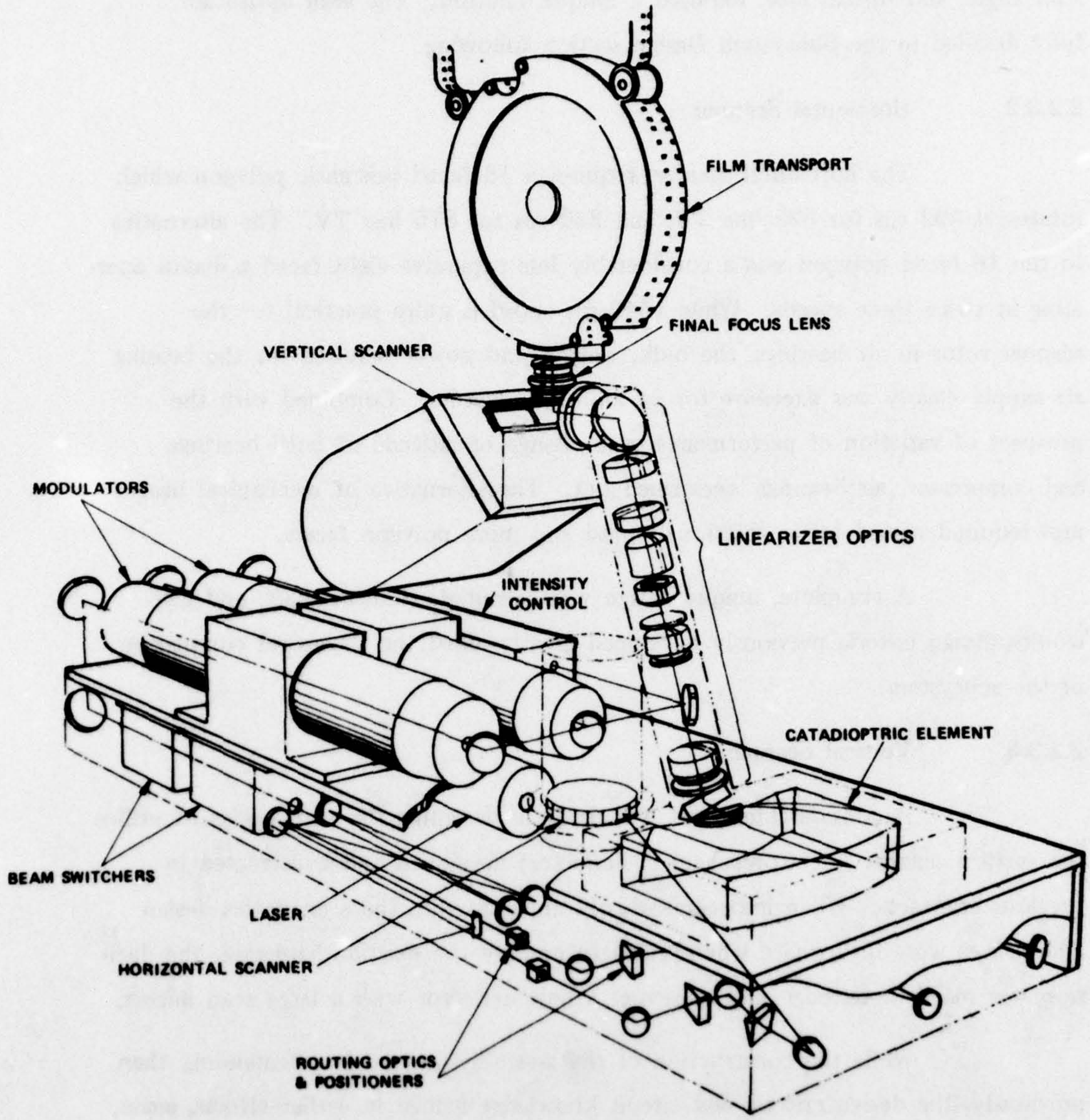


Figure 5 Optics Perspective

The scan optics, due to extraordinary requirements of pupil size, scan angle, and format size, required a unique solution. The scan optics are fully detailed in the Subsystem Design section following.

2.2.3.2 Horizontal Scanner

The horizontal scanner requires a 16 faced prismatic polygon which rotates at 492 rps for 525 line TV, and 820 rps for 875 line TV. The alternative to the 16 faced polygon was a considerably less expensive eight faced polygon operating at twice these speeds. While 1640 rps speed is quite practical for the scanner rotor in air bearings, the bulk, weight, and power required for the bearing air supply clearly was excessive for an airborne recorder. Combined with the prospect of variation of performance with change of altitude of both bearings and compressor, air bearings were ruled out. The alternative of mechanical bearings required use of lower rotational speed and more polygon facets.

A complete, unique design was executed. Motor, shaft, and electronics design criteria previously developed greatly aided the successful completion of the subsystem.

2.2.3.3 Vertical Scanner

A considerable effort was made in designing the scan optics to utilize the vertical scanner (electromechanical deflector) developed and constructed in previous contracts. When it became clearly apparent that the scan optics design alternatives were inadequate when scaled to employ the existing hardware, the decision was made to redesign and construct a new deflector with a large scan mirror.

While the construction of the assembly was no less demanding than previously, the design criteria and circuit knowledge gained in earlier efforts, again, appreciably contributed to successful completion of the subsystem.

2.2.3.4 Polygon Scan Corrector and Intensity Control

An acousto-optic modulator, of 1.5 MHz bandwidth, is employed in the optical train as a combined beam deflector and laser intensity control. The Bragg cell deflected beam transmission varies with the amplitude of the carrier

frequency; the angle of deflection varies with the frequency. While the application is reasonably straightforward, the unique circuitry to effect the control necessary in each aspect required full development.

2.2.3.5 **Beam Switcher**

A pair of acousto-optic modulators, similar to that employed as the intensity control, is used as a deflection system in each channel of the optical train. To attain continuous availability of the horizontal scan at video line rate, each channel requires two beams entrant to the horizontal scanner disposed one from the other by 22½^{o}. To prevent a beam which has completed a scan from continuing to write in the adjacent channel, in the side by side aperture configuration, the overscanning beam must be blocked when the active scan is completed.

The acousto-optic modulators are employed as deflectors in the optical path. By deflecting the appropriate beam at the proper time into the optical routing path, each beam scans only in the required aperture.

Again, while the application is relatively straightforward, the circuitry to effect precise control required unique treatment.

2.2.3.6 **System and Operating Control**

The system control synchronizes all subsystems to attain an optical output pictorial scan which precisely conforms to the electrical video signal input. The format and the signal encoding system of standard television are oriented to the highly mobile electron beam system of the CRT display. The integration of the video system with the electro-optical and high-inertia electromechanical components of the VLBR requires many unique solutions to achieve precise synchronization of all elements. Experience and design criteria gained from previous designs appreciably aided successful system integration.

Operating logic and control, while relatively straightforward, is, of course, unique to the recorder.

2.2.3.7 Film Transport

Investigation of all possible available transports for essentially a kinescope type application disclosed none which was suitable for airborne operation. The most promising approach for a transport which could attain rapid pulldown and high stability with a minimum of intricate mechanisms appeared to be the rolling loop film advance system. Bolstered by encouraging results, although incomplete, of a rolling loop type film transport under construction for an Air Force kinescope recording system, development of a rolling loop transport for the VLBR was undertaken.

A large proportion of the effort expended on the VLBR was devoted to the development of the rolling loop transport. It will suffice to state here that the rolling loop transport does not permit full realization of the outstanding performance of the rest of the recorder system. However, the physical arrangement of the recorder package does not preclude the use of other transports in the system.

The rolling loop transport is fully described in the Subsystem Design section following.

2.2.3.8 Audio System

The audio system, including amplifiers and light emitting diode and optical recording head for the dual channel system required unique configuration for this application.

2.2.3.9 Video System

The bandwidth requirement of the VLBR, hence the video system, is well beyond the bandwidth of commercial video systems. While expertise in commercial video was directly applied, the video system was designed and constructed to the performance and configuration requirements of the VLBR.

The video system and its components are described in detail in the Subsystem Design Section following.

2.2.3.10 Package and Enclosure

The structure and enclosure of the VLBR required unique treatment to house the supporting equipment and isolate the optical deck for excessive vibration. The problem was a relatively straightforward problem of engineering and arrangement.

Virtually all aspects of packaging were subordinate to other subsystem design and execution in tradeoff situation to conserve funds for the technically difficult developmental program. As a program policy, product engineering and packaging design were limited to the sound engineering practices necessary to attain specified performance in as compact a unit as possible with carefully selected commercial components. Typically, electronic chasses are constructed to Ampex commercial video equipment standards, instead of to avionics standards of compactness and component density. Available effort has been concentrated on proof of feasibility of recorder performance. As a result, the overall package is oversize and overweight, but not so much as to impair operational testing. Further, a future concerted product design effort can bring the package size and weight to within the specified limits.

2.4 System Design Parameters

The basis for the system design centers around a system analysis to determine the performance and design parameters of a system model which produces the specified results. In this model, it is necessary to derive the optical design parameters necessary to conform with the video signal format and the super-8 mm picture format.

2.4.1 Performance Parameters

To attain the specified résults, through the electrical and optical system onto the photographic film, the scanning spot size is determined by the spatial frequency response requirement that the modulation transfer factor shall be 0.5 for a test signal of 500 cycles per line. The system response for alternate black and white lines in the vertical direction must be T = 0.5.

The instrument-film performance is the convolution of the response functions of instrument and film. To determine characteristics of the instrument, the film characteristics must be defined and deconvolved from the system characteristics. The spatial frequency response of the recorder alone must be significantly better than the system response to allow for image degradation of the film. Degradation varies with film type, exposure level, object contrast, and film processing. System performance can be established only when film characteristics are prescribed.

On the basis of data furnished by WPAFB, the preferred film for this application is Eastman Kodak 3414 or 1414. The basic factors determining this choice are:

1) The film has a relatively high sensitivity (1 erg/cm^2 at 633 nm). To conserve laser space and power, the lowest sensitivity consistent with low granularity and high dynamic range is desirable.

2) The spatial resolution for recording 500 cycles per line on super-8 format must be 90 cycles per mm, at 70% MTF. Kodak 3414 film under proper processing appears to support the resolution requirement.

3) To satisfy the small area shading requirement, low film granularity is required (rms granularity = 9).

4) To yield a density range of 2.25 and a contrast of 200:1, a high dynamic range is required.

The 3414 aerial reconnaissance film appears to most nearly satisfy these requirements when exposed at high contrast and developed by Versamat processing. The film characteristics and processing are further discussed in the Subsystems Design section following.

2.4.2 Design Parameters

From the outset, the electronic system and electro-optic modulator were assumed to have flat response to 16 MHz. The signal frequency corresponding to 500 cycles per line at 875 lines, 30 frames per second is 15.8 MHz. The electronic response has a negligible effect on the spatial frequency response of the system.

The system performance, then, is predominantly determined by the convolution of optical system design performance with film characteristics. If the optical system is designed to have an MTF of 70% at 90 cycles per mm, the transfer function to film, with an estimated 70% MTF at 90 cycles per mm, would achieve the desired system transfer efficiency of 0.50 at 500 cycles per line or 90 cy/mm. The optical system then should be designed to have an MTF of 70% at 90 cy/mm; this implies a gaussian scan spot of 5.9 micron diameter (at the e^{-2} intensity level).

The film exposure for a 100% modulated beam is equivalent under the above assumptions to an object contrast of 5.7. The product of film MTF with optical MTF is 0.5. If the input modulation is reduced to 0.33 at 15.8 MHz, target object contrast drops to 1.6/1.

To determine beam size, the diffraction limited scan spot must be smaller than 5.9μ to allow for depth of focus tolerance and optical observations. Assuming a 5 μ diffraction limited spot size and a 633 nm laser wavelength, the ratio of image distance to input beam diameter at the spot forming lens is 6.2.

The effective image distance of the spot imaging system, is determined by the scan line length (5.61 mm) and the angle scanned by the beam (18.75°), yielding an optical system focal length of 17.16 mm. The beam size entering the catadioptric relay system must be 2.74 mm.

Recorder system design parameters are:

Format	Dual super-8mm; 4.21 x 5.61 mm frames side by side on 8 mm centers.
Input	30 frames per second, 525 or 875 line video, 16 MHz bandwidth, two channel.
Frame rate	30 frames per second, 60 fields per second, 2:1 interlace.

Film	16mm Kodak 3414 aerial, reconnaissance negative film, 2R1667 (1-3).	
Scan polygon	16 faces	
Input beams	4	
Input beam angle total	48.75°	
Input beam angle per channel	22.5°	
Input scan angle per channel	18.75°	
Beam diameter at polygon	2.74 mm	
Beam diameter at vertical deflector	5.48 mm	
Catadioptric relay focal length	38 mm	
Linearized relay focal length	76 mm	
Final focus lens focal length	34 mm	
Vertical deflector beam scan angle	7.05°	
Vertical deflector scan angle	3.53°	
Lines per frame interval	525	875
Active lines per frame	483	804
Transport pulldown time	2.0 ms	2.0 ms
Raster line spacing	8.8μ (347 μin)	5.3μ (209 μin)
Scan spot diameter	6μ (236 μin)	6μ (236 μin)
Line rate	15750 per sec.	26250 per sec.
Scanner speed	29,531.25 rpm	49,218.75 rpm
Optical MTF at 0.7	54 cy/mm	90 cy/mm

The optical system design is discussed in detail in the Subsystem Design sections following.

SECTION III
SUBSYSTEM DESIGN

The discussion of components following presumes reader knowledge of the fundamental principles of the various devices. Description and discussion is limited to function and performance in the VLBR System.

3.1 Optical System

The basic parameters of the optical system design, listed in Section 2.4.2, are derived from the interrelation of fundamental requirements of continuous writing scanners, the picture format, and the video line rate. As noted in Section 2.4.1, System Parameters, a modulation transfer efficiency of 50% from video to film for a video signal of 500 cycles per frame line requires a 633 nm. wavelength scanning spot of 6 μm (236 μ in.) diameter to the e^{-2} intensity level. The effective ratio of image distance to beam diameter at the spot forming lens is 6.2. The optical system is designed to these parameters to attain the transfer efficiency required.

3.1.1 System Design

The recording raster scan design requires a stationary film at the focal position during recording of each frame. The film is immobilized at the focal position during recording of each frame. The film is indexed by the rapid pulldown mechanism of the film transport during the vertical blanking interval between frames. Each horizontal line of the raster is generated by reflection of the modulated beam off each face of a high speed rotating polygon driven in synchronism with the video signal. The raster and interlace are generated in the vertical direction by the galvanometer deflector interposed in the optical system.

The video signal format has a 16 - 18% blanking period at the end of each line transmitted, after which the next line is transmitted, implying a scan

duty cycle of 82%. To optically attain an 82% mechanical scanning duty cycle, an essentially continuous writing or 100% duty cycle configuration is required.

Continuous writing beam scanning by rotating polygon is attained when the relationship of angular separation of scan beams and the scan line length is arranged so that, at the termination of scan by one beam, the succeeding scan beam is in position to write the succeeding line. The relationship for continuous writing is

$$\theta_{cw} = \frac{2 \times 360^{o}}{FN}$$

where θ = cw scan angle

F = number of polygon facets

N = number of input beams included in angle θ

The number of combinations is limited by practicality of scanner and scan lens systems. A minimum of two beams, disposed angularly equal to the polygon external angle, are required for continuous, unvignetted scanning. From the design parameters, Sec. 2.4.2, at 30 frames per second and 875 lines per frame, 26250 scans per second are required. As a practical maximum, ball bearing scanners intended for continuous duty should be limited to under 1000 RPS rotational speeds. The minimum number of polygon faces required under these constraints is:

$$\frac{26250 \text{ scan/sec.}}{2 \text{ scan/face} \times 1000 \text{ rev/sec.}} = 13.125 \text{ face/rev.}$$

A sixteen faceted polygon, rotating in ballbearings at 492.1875 RPS at the 525 line video rate, and rotating at 820.3125 RPS at the 875 line video rate, provides the horizontal scan rate necessary.

The picture format of Figure 2 implies a spatial deadspace between side by side frames of 28% of the horizontal scan interval, whereas the video format allows only 16% dead time between scans. A single scan beam, therefore, cannot scan both frames in sequence; each frame requires its own set of modulated beams, properly placed, to record the format simultaneously. A four beam system is therefore required. To conform to the optical system design parameters generated in Section 2.4.2, an input beam arrangement shown in Figure 6 was employed. The 1 beams write in succession in one frame position, while the 2 beams write on the

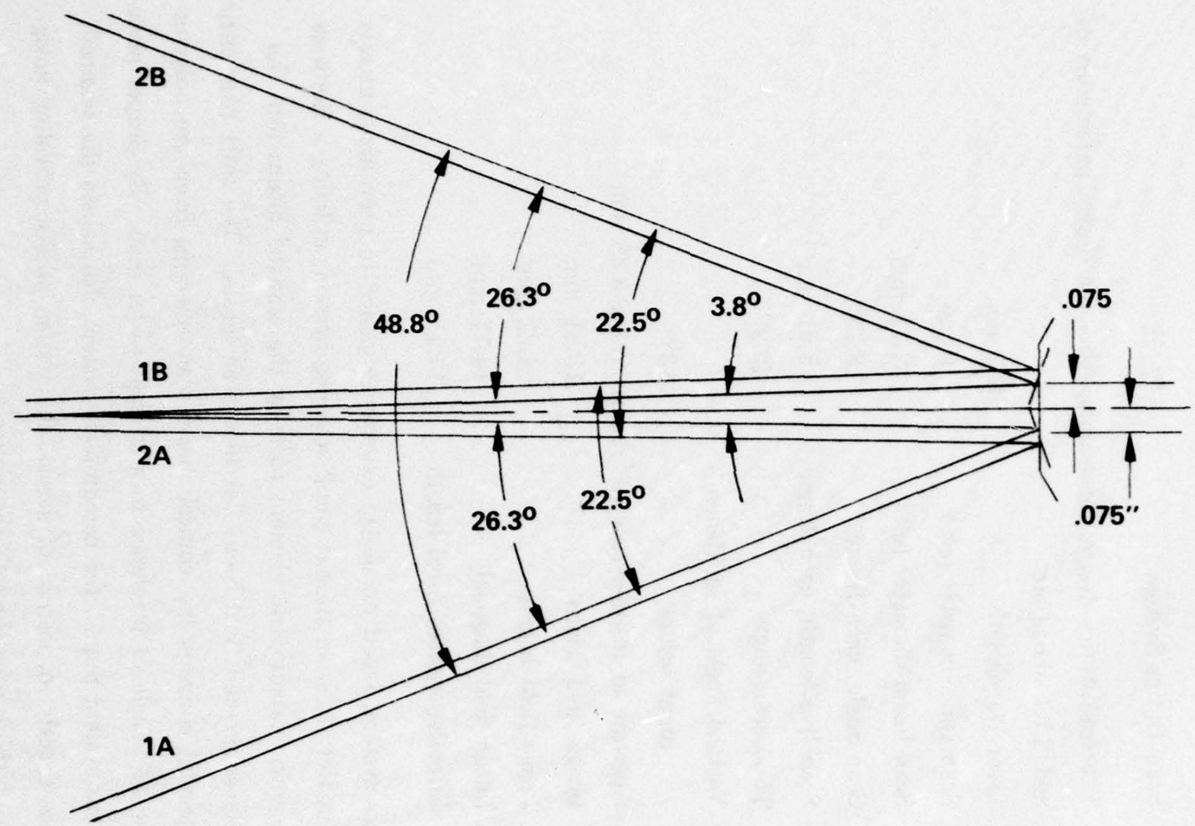


Figure 6 Input Beam Arrangement

other. The total input beam angular subtense for the optical system is seen to be 48^{o} - 45'. These constraints, then, define the scan optics requirements, and limit the available design degrees of freedom.

3.1.2 Scan Optics System

The scan optics design constraints, from the design parameters of Section 2.4.2, and 3.1.1 above are:

Laser Wavelength	633 nm
Scan spot diameter (e^{-2})	6 μm
Scan beam diameter (e^{-2})	2.74 mm
Scan angle, each frame	18.75^{o}
Scan line length, each frame	5.61 mm
Total scan angle	45.2^{o}
Vertical angle of incidence, input beams	13^{o}
Aperture at scanner face (e^{-4} diam)	7.4 x 3.88 mm
Image field width	13.51 mm
Image field height	4.21 mm
Image field diagonal	14.17 mm
Effective system focal length	17.15 mm

The scan optics system, based on design experience gained in previous contracts and reported in Ref. 2, is an entrant pupil scanning system, utilizing a Bouwers-Maksutov concentric catadioptric element to relay the scanned beams into the pupil of the linearizer and final focus flat field scan lenses. The solid concentric catadioptric element converts the conical beam scan emerging from the polygon scanner face at 13^{o} angle of incidence to a straight raster scan. By proper placement of the lens system pupils, the catadioptric system also causes the scanned beams to rotate exactly in, instead of across, the system pupils, providing unvignetted passage of the beams through the optics.

To provide an unvignetted and diffraction limited flat field optical system which can accommodate a mechanical oscillating mirror vertical scanner,

a relay system was designed to provide collimated light at the vertical scanner. With the vertical scanner as a pupil in the system, the final focus lens was designed as an external pupil flat field lens to preserve the unvignetted, diffration limited imaging qualities of the system.

The scan optics design, after consideration of many optical and physical configuration tradeoffs, resulted in the following system parameters:

Catadioptric element focal length	38 mm
Linearizer focal length	76 mm
Final focus lens focal length	34.286 mm
System focal length	17.143 mm
System speed	f/2.3

The general recorder requirement for compactness of the system considerably complicated the optical system design. Concurrent with the scan optics design, the recorder system optical and structural design was progressing. The scan optics system, configured to optimize space requirements and arrangement of the total optical system is shown in Figure 7.

3.1.3 Optical System

The optical system consists of active and passive components organized and operated to produce the modulated, flat field scan spot at the transport film plane. The optical system diagram is shown in Figure 8. The physical arrangement of the optical deck is shown in Figure 9.

3.1.3.1 Laser

The laser selected as a radiation source for the VLBR is a 3 milliwatt ruggedized helium-neon laser, radiating at 633 nm. The selection was based on the radiation power required, the reliability and durability of the hardware, and the adaptability of the hardware to the recorder configuration.

The power required for recording is dependent on recording media sensitivity, exposure time during scanning, and radiation power attenuation through the optical system.

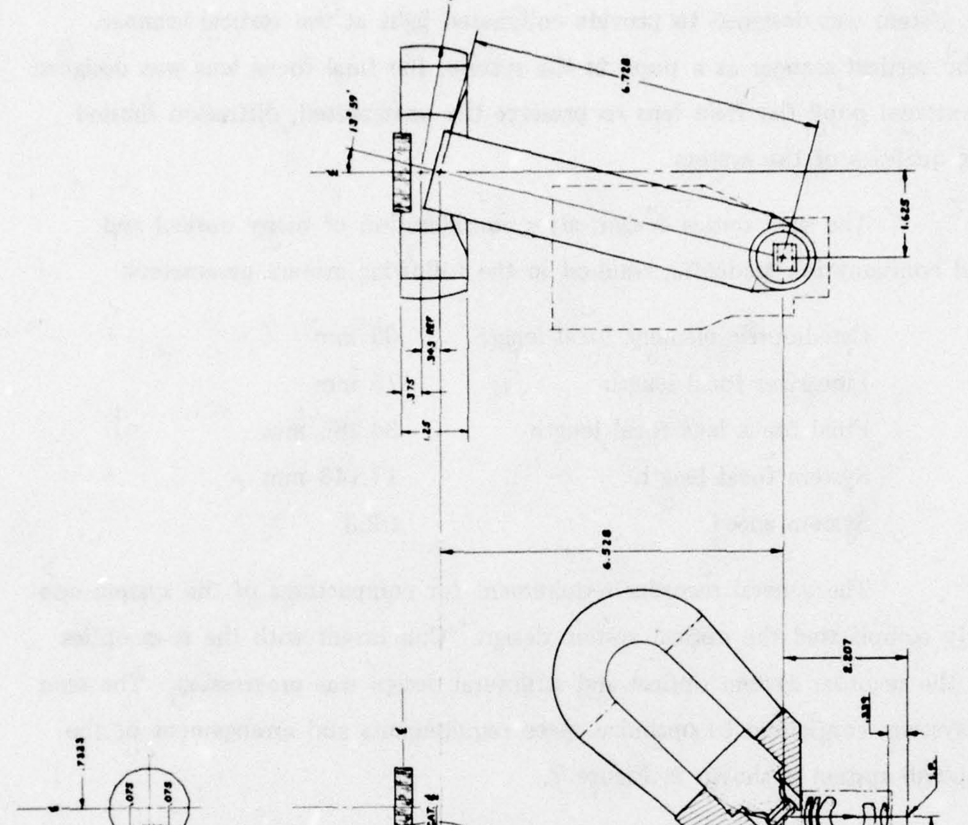
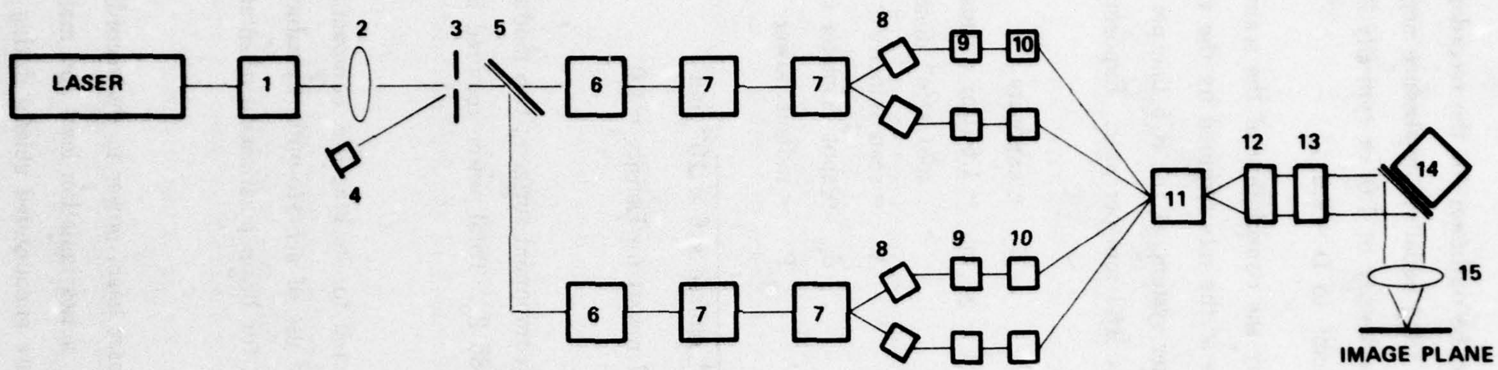


Figure 7 Scan Optics System



1. Scan Corrector-Intensity Control
2. Beam Conditioning Lens
3. Intensity Control Beam Splitter
4. Intensity Control Beam Detector
5. 50-50 Beam Splitter
6. Acousto-optic Modulator
7. Beam Switcher
8. Beam Position Corrector
9. Horizontal Beam Angle Corrector
10. Vertical Beam Angle Corrector
11. Horizontal Scanner Polygon
12. Catadioptric Relay Element
13. Linearizer Element
14. Vertical Scanner
15. Final Focus Lens

Figure 8 Optical System Diagram

The recording media, judged to be optimum for the recorder, as indicated in Section 2.4.1 is Kodak 3414 or 1414 aerial reconnaissance negative film. Sensitivity is 1 erg/cm^2 to expose to a density of 1.0, or typically 3 ergs/cm^2 to reach a density of 2.0, 6.3 ergs/cm^2 to D = 2.6.

Exposure time is determined by the convolution of the scanned gaussian spot scanned across its power profile at the rate required by the video line rate and the line length. For the recorder system, at the 875 line per frame, 30 frame per second rate, the scan velocity is .183 mm per μsec. Exposure required is:

$$E = m_n \left(\frac{P}{Vd_n}\right)$$

where

E = exposure

m_n = 1.60 for a gaussian spot at e^{-2} diameter

V = scan velocity

d_n = spot diameter (e^{-2})

P = radiant power

$$1 \text{ erg/cm}^2 = 1.60 \left(\frac{P}{1.83 \times 10^4 \text{ cm/sec} \times 6 \times 10^{-4} \text{ cm}}\right)$$

P = 7 erg/sec = .7 μwatt = .0007 mwatt for Density = 1.0

P = .0021 mw for D = 2.0

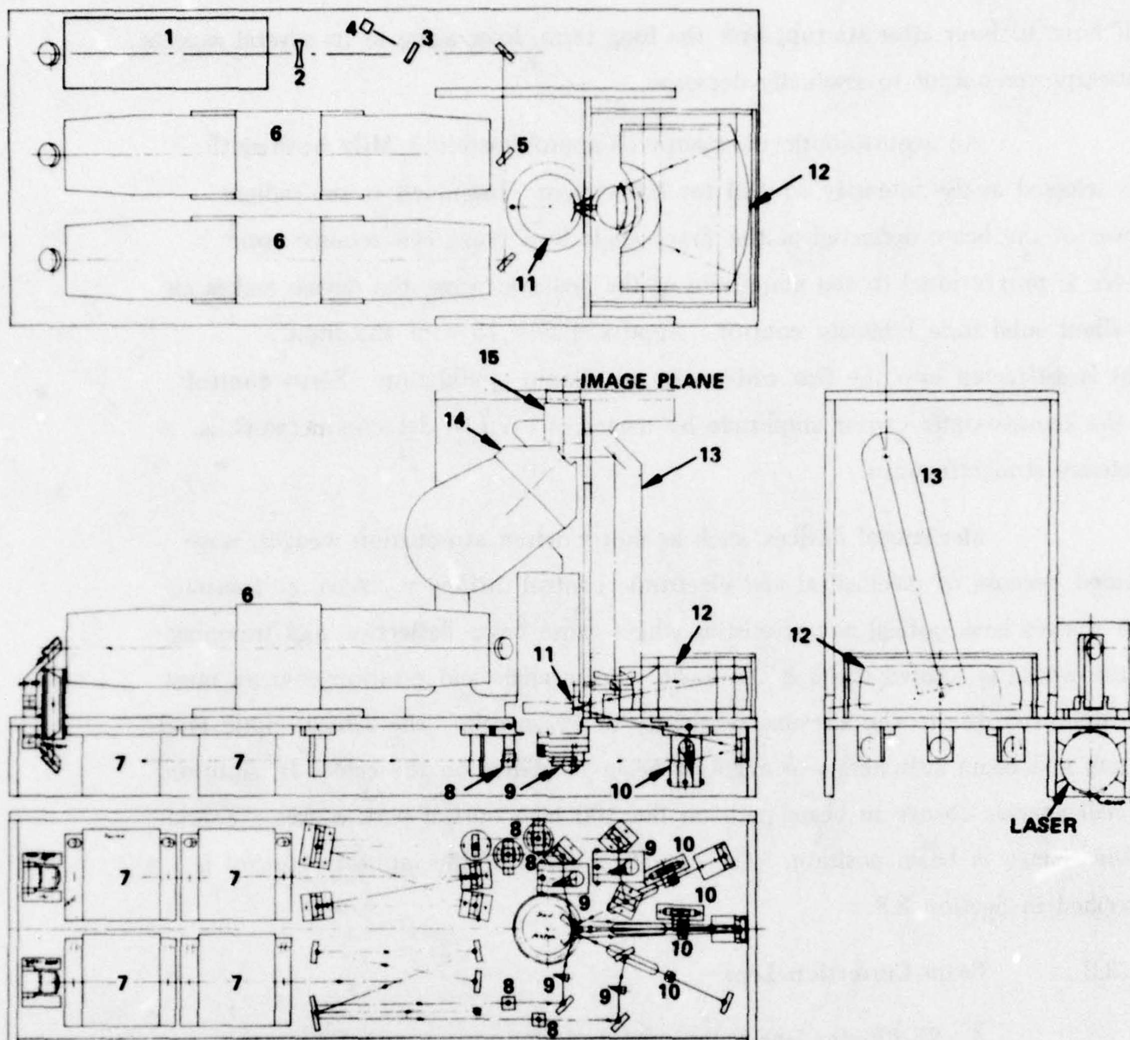
Optical attenuation through 62 component surfaces, two modulators, a beam splitter, and two beam switchers is .0085 P_O. Total power required is

$$P = \frac{2.1 \times 10^{-3} \text{ mw}}{8.5 \times 10^{-3}} = .25 \text{ mw}$$

The helium-neon laser was selected for its long life, compact head and power supply, and adequate output. The use of acousto-optic transducers in the system precluded the necessity for accounting for beam polarization orientation.

3.1.3.2 Intensity Control

To maintain a preset level of laser beam power in the recording system, an intensity control is required which senses radiation level and maintains the desired level. Variations in laser output are encountered chiefly during the first



1. **Scan Corrector-Intensity Control**
2. **Beam Conditioning Lens**
3. **Intensity Control Beam Splitter**
4. **Intensity Control Beam Detector**
5. **50-50 Beam Splitter**
6. **Acousto-optic Modulator**
7. **Beam Switcher**
8. **Beam Position Corrector**
9. **Horizontal Beam Angle Corrector**
10. **Vertical Beam Angle Corrector**
11. **Horizontal Scanner Polygon**
12. **Catadioptric Relay Element**
13. **Linearizer Element**
14. **Vertical Scanner**
15. **Final Focus Lens**

Figure 9 Optical Deck Arrangement

half hour to hour after startup; over the long term, laser aging in its several aspects causes power output to gradually decrease.

An acousto-optic modulator of approximately 1 MHz bandwidth was selected as the intensity control for the system. Inasmuch as the radiant power of the beam deflected at the Bragg angle in a Bragg cell acousto-optic device is proportional to the amplitude of the acoustic wave, the device makes an excellent solid state intensity control. Approximately 75% of the input light is diffracted into the first order with maximum modulation. Servo control of the acousto-optic carrier amplitude by means of a P.I.N. detector network is relatively straightforward.

Mechanical devices, such as motor-driven attenuation wedges, were avoided because of mechanical and electronic control difficulty. Also, all transmission wedges have optical characteristics which cause beam deflection and tramping as the wedge is rotated through the beam. Beam angle and position changes must be minimized due to the extreme sensitivity of Bragg cells – the acousto-optic modulators and beam switchers – to angle of beam incidence on the cells. In addition, a small angular change in beam path on the 100 inch optical path causes a considerable change in beam position. The operating detail of the intensity control is described in Section 3.8.

3.1.3.3 Beam Correction Lens

A -.25 diopter lens is interposed in the optical path behind the intensity control to size the laser beam to a 1.9 mm diameter at the entrance to the acousto-optic modulators. Unless the substantially collimated beam meets this requirement, the acousto-optic modulators may suffer a serious reduction in bandwidth capacity or light transmission, depending on the condition of the entrant beam.

3.1.3.4 Intensity Control Detector

Four percent of the unmodulated beam is diverted to a P.I.N. diode detector. The detector provides the beam level sensing to servo control the intensity control.

3.1.3.5 **Beam Splitter**

Just ahead of the acousto-optic modulators, the unmodulated beam is divided into two paths of equal intensity by a dielectric coated beam splitting mirror.

3.1.3.6 **Acousto-Optic Modulators**

The electrical to optical transducers in the system which convert the modulated video electrical signal to modulated video optical signal are acousto-optical modulators. The modulators are Datalite DLM-20 Bragg cell type modulators. The laser beam is diffracted at the Bragg angle proportional in intensity to the signal amplitude of an 80 MHz acoustic wave carrier modulated by the video signal. The unmodulated input beam is, therefore, divided into an undeflected, or zero order, beam and a diffracted, or first order, beam. The zero order beam is masked off and rejected; the first order beam is routed into the scanning system.

The passband of the modulator is virtually flat to 9 MHz, but transfer efficiency is -3 dB at 14 MHz and -6 dB at 20 MHz. To attain a flat system signal response to 16 MHz, pre-emphasis of the video signal is provided beyond 9 MHz to achieve the flat system response. The electronic compensation system and modulator performance is discussed in Section 3.5.

The bandwidth of an acousto-optic modulator is limited by the transit time of the acoustic wave through the beam acted upon. To attain the rated bandwidth, the DLM-20 requires a 1.9 mm diameter beam (at the e^{-2} intensity level) as an input. The beam is reduced through telescope optics to produce a 0.1 mm. beam in the working section of the acousto-optic modulator crystal. The emerging beams are restored by an expanding telescope of identical (nearly) proportions to the original 1.9 mm beam size at the output.

The effect of the telescope reducing and expanding optics in the modulator system renders the device critically sensitive to angular and lateral beam routing, and routing changes. Although the device performs to specifications when the stipulated input conditions are precisely met, slight variations in beam size and perturbations to the input path significantly affect performance.

Too large a beam results in truncation of the gaussian energy distribution, with resulting aperture induced interference patterns. In addition, internal reflections render the output beam confused and of limited value. Too small a beam results in a diffraction limited beam size through the crystal which is considerably larger than the 0.1 mm diameter necessary to attain the bandwidth specifications. Convergence or divergence of the input beam similarly affect the system response.

The effect produced by the back to back beam reducing and expanding optics also preclude the use of the acousto-optic intensity control as a polygon face error correction deflector. The intensity control, located ahead of the modulators in the optical path, was intended to provide a programmed 20 arc second maximum beam deflection through the system to compensate for polygon face pyramidal error. However, the 20 arc sec. angular beam change, which produced a .006 mm lateral beam translation at the modular input, when processed through the telescope optics, produced a 0.9 mm beam displacement at the exit. In addition, the internal optics vignetted the beam in any position off-axis. The intensity control in the position allocated could not be used for polygon correction because of the effect of the modulator optics on the throughput beam.

The sensitivity of the Bragg cell to angular approach of the beam to the acoustic grating requires essentially micrometer adjustment of lateral and angular positioning of the unit in the beam. The mechanical arrangement of the Bragg cell internal adjustment also requires precise adjustment to maximize the output.

Once aligned, the modulators performed to full specification. At maximum modulation, approximately 70% of the input beam is diffracted into the first order, or useable beam.

3.1.3.7 Beam Switchers

As noted in Section 3.1.1, each picture channel requires two input beams carrying the same information to provide continuous writing scanning on each frame. After emergence from the acousto-optic modulator, the modulated beam must be divided and precisely routed to the scanner. However, each beam is scanned

over a path considerably longer than the assigned frame width, so that unless the scan beams are gated off before and after writing an information line, the beams will overscan into the adjacent frame.

A pair of acousto-optic modulators, employed as deflectors, are used to gate the beams and divide the input beam into two optical paths, as shown diagramatically in Figure 10. The modulators used are Datalight DLM-1, modified to pass a 6 mm diameter beam. The modulators are driven by a carefully regulated and stable 45 MHz oscillator and driver system. This results in the emergence of two beams, separated angularly by 7 milliradians. By placing two such modulators in tandem, oriented so that the input or zero order beam is at the Bragg angle of the acousto-optic cells, but arranged to route the first order deflected beams to opposite sides of the zero order, the modulated beam is effectively split into two beams separated angularly by 14 milliradians, under electronic control. The cells are alternately energized in synchronism with video to provide alternate line scan.

Performance and circuitry for the components are described in Section 3.8.

3.1.3.8 Routing Optics

The optical path of each channel has some 25 passive optical elements inserted between the laser and the horizontal scanner for the purpose of directing the beams to and through the active elements. All mirrors are flat to $\lambda/20$; transmissive elements are flat to $\lambda/10$. Mirrors are dielectric coated for 99% reflectivity at the appropriate angle of incidence; transmissive elements are antireflectance coated to attain 99.5% transmission.

All routing optics mounts are fully constrained, and are designed to have a natural frequency of over 1000 Hz.

The routing optics shown in Figure 9 between the beam switchers (7) and the horizontal scanner polygon (11) route and position the four information beams at the required angle and location onto the scanner.

In the scan optics system, subsequent to the horizontal scanner, the relative angles at which the beams enter the optics determine the relative positions of the scanning spots at the output image plane of the system. To align the beams angularly so that the line start and line to line correspondence of the pairs of scanning spots can be set to within .25 spot diameter or 59 μ in. (1.5 μm), routing optics are organized to provide variation of alignment ranging from 3^{o} to 15". Coarse adjustment is made horizontally by pivoting routing mirrors about a locator pin center; vertical adjustment is made by shims placed in appropriate locations to tilt the mirror.

Fine adjustment, horizontally and vertically, is made by tilting the vernier adjust prisms (9 & 10, Figure 9). Changing the angle of the prism in the approaching beam causes the angular deflection of the beam to change by approximately .02 to .08 of the angular change of the prism.

Once the angular relationship of the beams in the system is established, beams may arrive at the scanner polygon face (which is the entrance pupil of the scan optics system) sufficiently displaced in position to cause partial relay of the beam by the scanner, and vignetting through the subsequent pupils in the system. Parallel plates, movable horizontally and vertically, in each beam path (item 8, Figure 9), shift the beam in position without disturbing the angular relationship.

3.1.3.9 Scan Optics

The scan optics, the design of which is described in Section 3.1.2, consists of the catadioptric relay element, the linearizer periscope, and the final focus lens, placed in the relationship shown in Figure 7.

The horizontal scanner polygon scans the four input beams into the catadioptric element which focusses the scanned beam to a spot scanning radially in a horizontal plane. The spot scan radius is equal to the catadioptric element focal length (38 mm), centered on a line passing vertically through the center of the catadioptric element surface radii. The linearized relay system converts the curved planar input spot field to a flat field focal beam, with pre-distortion to scan the beam into the final focus lens to produce a scan whose length is proportional to polygon scan angle.

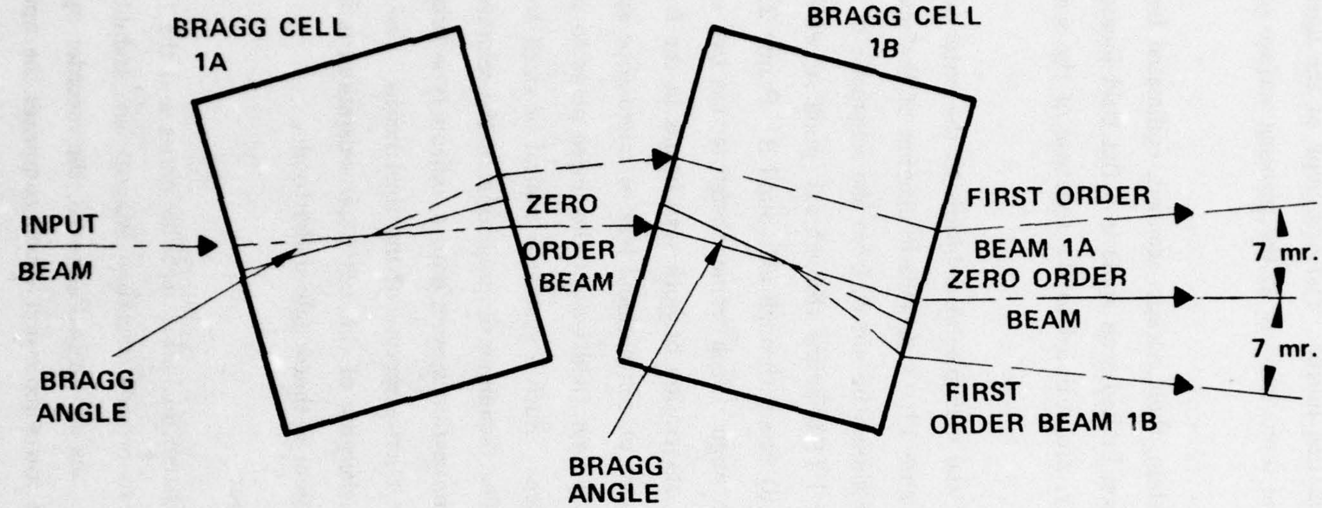


Figure 10 Beam Switcher Arrangement

The linearizer and final focus lens are separated sufficiently to provide space for the vertical scanner oscillating mirror. The exit pupil of the linearizer and the entrance pupil of the final focus lens are at the pivoting surface of the vertical scan mirror.

The scan optics system, then, accepts scanned, collimated beams and produces unvignetted, diffration limited scan spots in a flat field located linearly, horizontally and vertically, proportional to the timebase of the scan within 0.1%.

The relationship of the multiple input beams to the raster scans at the image plane is shown in Figure 11. A schematic diagram of the scan optics system is shown in Figure 12. It should be noted, from the schematic of Figure 12 that one beam scanning frame 1 (1A) passes through exit pupil A, while the second beam scanning frame 1 (1B) passes through exit pupil B. Frame 2, also, has one scan passing through each pupil. Each frame, therefore, has two exit pupils, a fact which makes direct observation of both scan beams in the frame difficult, if not impossible, by means of conventional lens or microscope systems. Physically, the separation requires a large field lens at the image plane to route the illumination into an imaging lens. Such a system is typical of small format, high aperture projection lenses. The technique of projection of the scanned image at the film plane by means of a projection system onto a vidicon type tube became the technique used to observe the micro-structure of the final image. The use of microscope to examine the image, because of the exit pupil separation, is in most instances misleading unless the system is thoroughly understood.

3.1.3.10 Structure and Layout

The total optical system, including recorder optics and the film transport, is structurally arranged to provide structural integrity and stability of the system up to the film plane. As shown in Figure 13, the recorder optical system is contained in a base and tower extension which comprises the optical deck. The film transport is rigidly bolted and pin located at the upper face of the optical deck tower, but can be easily demounted when required.

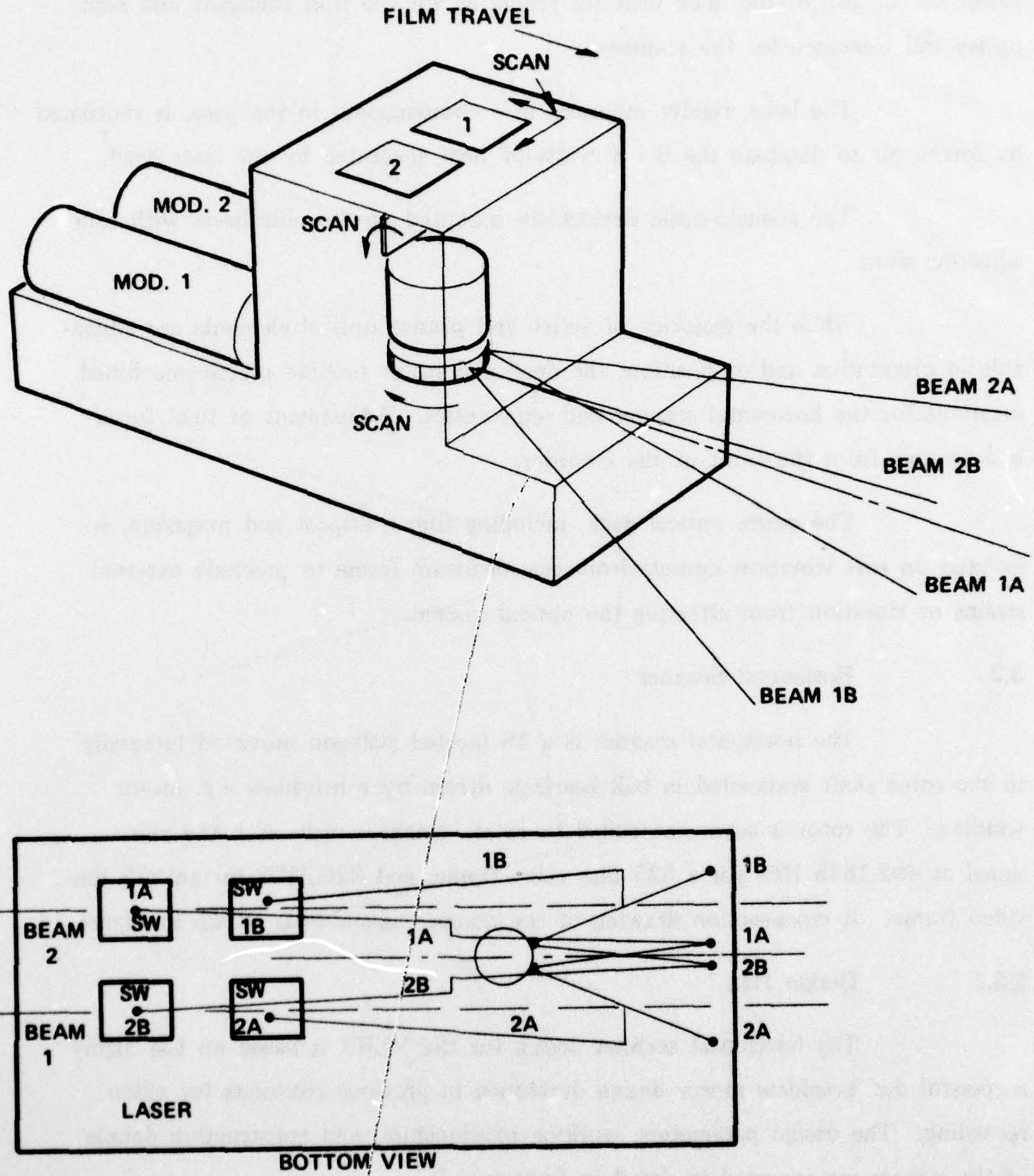


Figure 11 VLBR Writing-Scanning Relationships

The basic structural member of the optical deck is the box-like base which mounts the majority of the optical elements on or in it as indicated in Figure 9. The base is a closed box shell, which inherently provides the flexurally and torsionally stiff optical bench essential to the precision laser recorder. The structural tower on the top of the deck provides mounting for the film transport and scan optics and clearance for the scanners.

The laser, rigidly mounted in a compartment in the base, is ventilated by forced air to dissipate the 6 - 8 watts of heat generated by the laser head.

The acousto-optic devices are mounted on movable bases with cam adjusting slots.

While the majority of active and passive optical elements are adjustable in orientation and/or position, the deck and tower provide precise machined locations for the horizontal scanner and scan optics. Adjustment of final focus is accessible from the front of the recorder.

The entire optical deck, including film transport and magazine, is isolated on soft vibration mounts from the enclosure frame to preclude external strains or vibration from affecting the optical system.

3.2 Horizontal Scanner

The horizontal scanner is a 16 faceted polygon mounted integrally to the rotor shaft suspended in ball bearings, driven by a brushless d.c. motor winding. The rotor is servo controlled to rotate synchronously with the video signal at 492.1875 RPS for a 525 line video frame, and 820.3125 for an 875 line video frame. A cross-section drawing of the scanner assembly is shown in Figure 14.

3.2.1 Design Plan

The horizontal scanner design for the VLBR is based on the highly successful d.c. brushless motor design developed in previous contracts for video recording. The design parameters, working relationships, and construction details of the system are reported in detail in Reference 2.

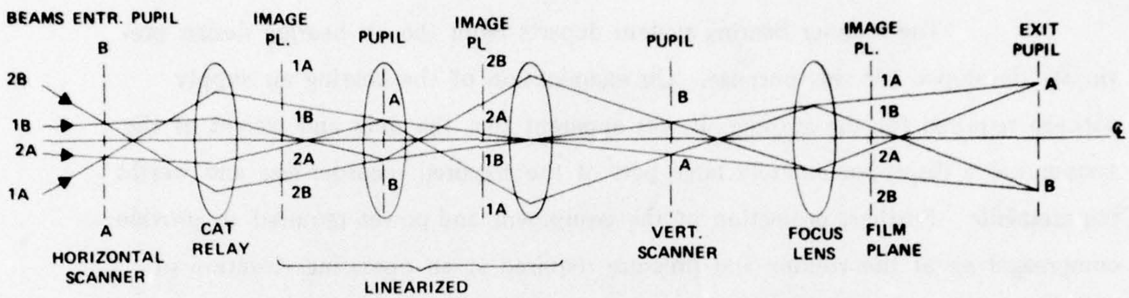


Figure 12 Schematic Diagram Scan Optics System

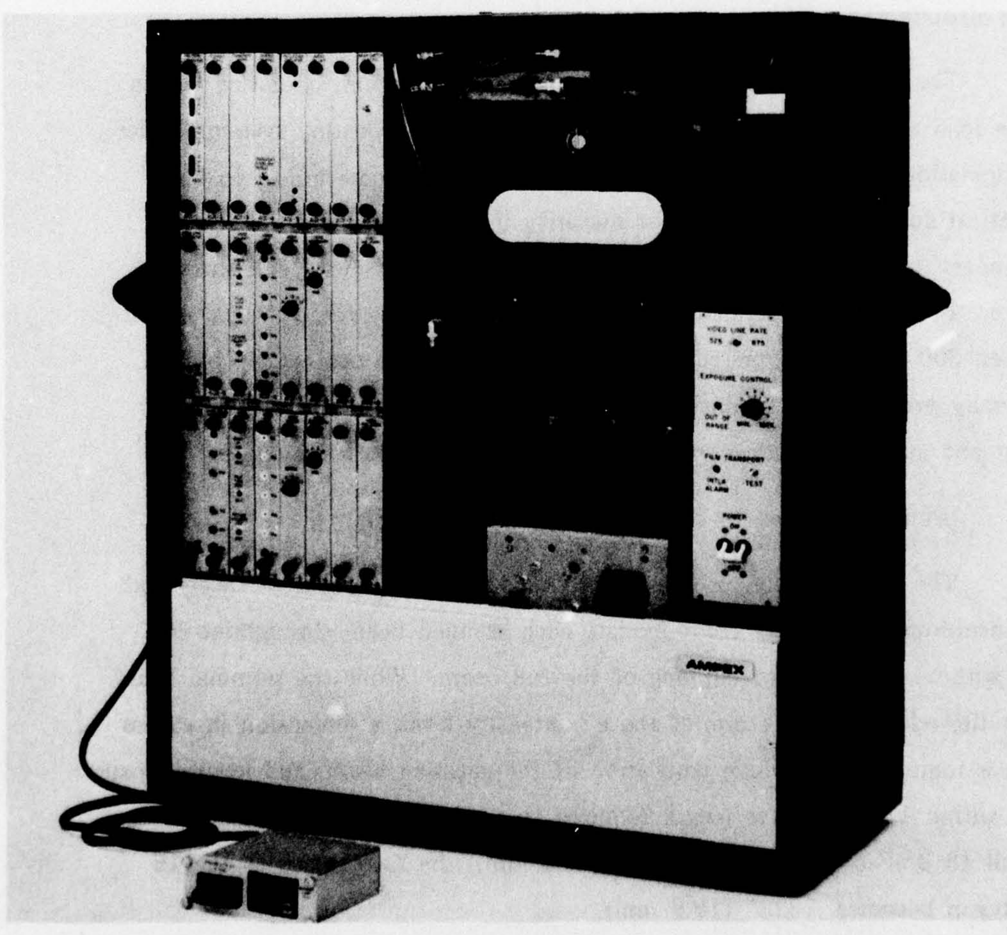


Figure 13 Optical Deck & Camera

The scanner polygon, to satisfy optical and mechanical design requirements detailed in Section 3.1.1, is a 16 faceted prismatic polygon rigidly mounted to a heat treated 38% cobalt steel rotor shaft.

The scanner bearing system departs from the air bearing design previously developed for this purpose. On examination of the bearing air supply package required for the scanner, it was apparent that the bulk and weight of the system was a disproportionately large part of the required recorder size and weight requirements. Further, projection of the equipment and power required to provide compressed air at the volume and pressure required at an operating elevation of 25000 ft. indicated increase in size from the prototype. Beyond this, a complete reassessment of the design and performance of the air bearing system at a 25,000 ft. pressure altitude appeared to be mandatory.

For these reasons, a ball bearing suspension system, operating within conservative load and speed limits, was chosen as the scanner bearing system. Under critical examination, the runout and power requirements were determined to be within practical design limits. The major disparity in the system is durability. Ampex scanners in air bearings have run several thousand hours with full specified performance. Ball bearings operated in the scanner will usually require replacement with between 300 and 600 hours running. However, failure is not catastrophic, but is generally preceded for a considerable period of evidence of increased power requirement and audible deviation from the normal quiet, smooth operation.

3.2.2 Scanner Polygon

The scanner polygon size is determined by the number of facets and the face dimensions required to accommodate each scanned beam throughout the scan angle without occlusion or clipping of the full beam. While the nominal beam diameter at the scanner is 2.74 mm at the e^{-2} intensity level, a dimension in excess of 4.3 mm is required to preclude truncation of the gaussian beam, and keep exposure uniformity within 1%. The face length required to retain the full beam diameter over the full 18 3/4° of beam scan is .283" (7.2 mm); the face radius of the 16 faceted polygon becomes .7323" (18.6 mm).

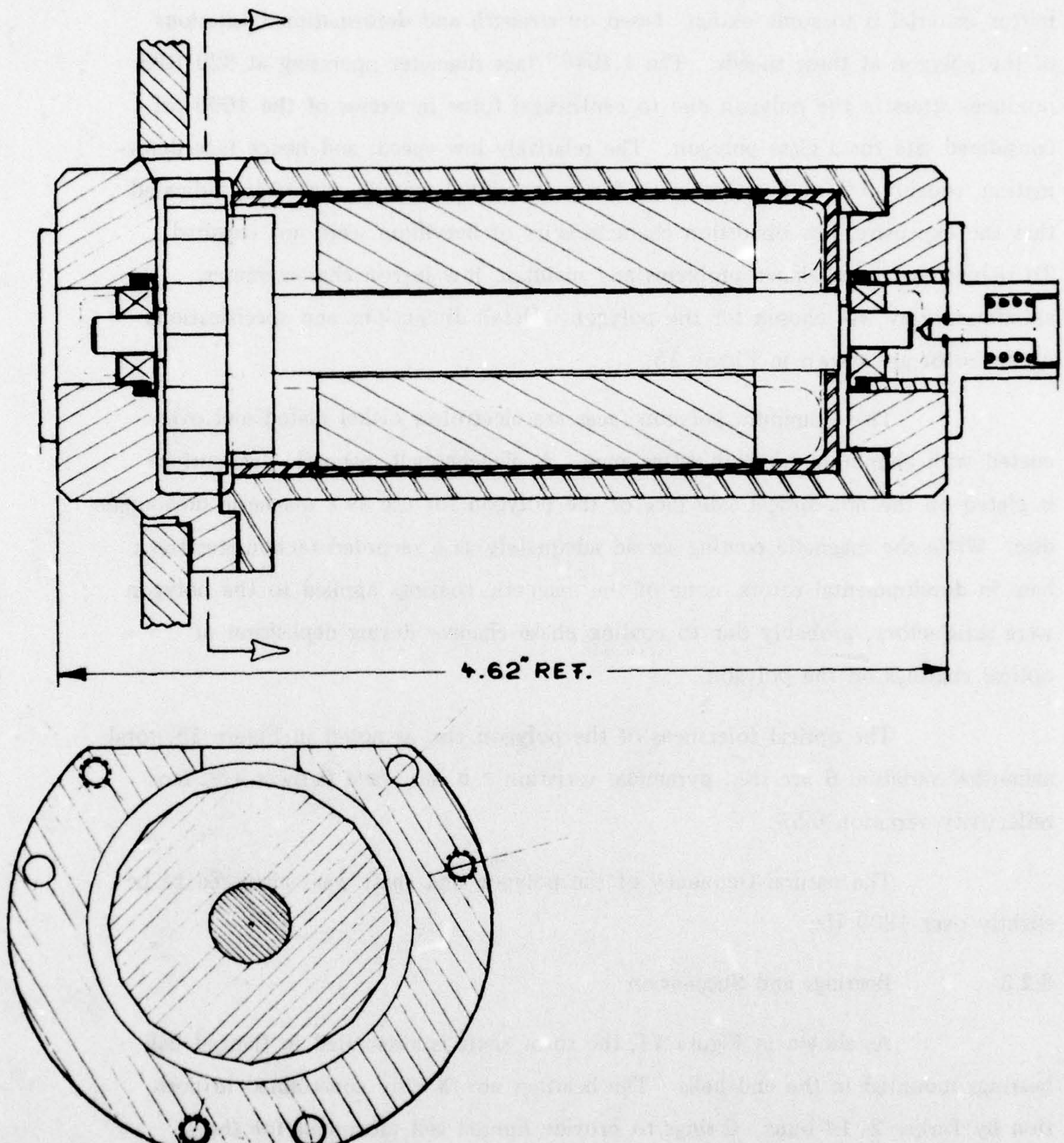


Figure 14 Horizontal Scanner Assy. Section

As previously noted, the polygon must rotate at 492.1875 RPS at the 525 line rate and 820.3125 RPS at the 875 line rate. The choice of mirror material is to some extent based on strength and deformation limitations of the polygon at these speeds. The 1.4646" face diameter operating at 820 RPS produces stress in the polygon due to centrifugal force in excess of the 1000 psi considered safe for a glass polygon. The relatively low speed, and hence face deformation, roughly 1/5 of bursting speed for conventional metallic materials, indicated that the expensive, low distortion characteristics of beryllium were not required. To reduce dynamic balance problems and maintain low inertia characteristics, aluminum alloy was chosen for the polygon. Detail dimensions and specifications of the rotor are shown in Figure 15.

The aluminum polygon faces are electroless nickel plated and overcoated with aluminum for high reflectance. A nickel-cobalt magnetic disc surface is plated on the non-optical side face of the polygon for use as a magnetic tachometer disc. While the magnetic coating served adequately as a recorded tachometer track base in developmental rotors, *none of the magnetic coatings applied to the polygon* were satisfactory, probably due to coating phase changes during deposition of optical coatings on the polygon.

The optical tolerances of the polygon are, as noted in Figure 15, total azimuthal variation 6 arc sec., pyramidal variation $\pm$ 5 sec.; face flatness $\lambda/8$; face reflectivity variation 0.5%.

The natural frequency of the polygon and shaft was calculated to be slightly over 1300 Hz.

3.2.3 Bearings and Suspension

As shown in Figure 14, the rotor shaft is suspended in flanged ball bearings mounted in the end bells. The bearings are flexibly constrained in position by Parker 2- 14 buna O-rings to provide limited self-alignment for the bearings, and to provide high frequency vibration damping. The bearings are Barden SFR3FFTA ABEC-7 high speed instrument bearings lubricated with MIL-G-3278 grade synthetic grease. The bearings carry approximately 16 oz. (453 gr.) of preload to assure stable operation at speed.

3.2.4 Motor

The scanner motor is similar in design to the motor system developed in previous contracts, and reported in Reference 2. Motor shaft material, as before, is Simonds #3500 38% cobalt steel heat treated to 62 R_C. Stator laminations, as previously, are Carpenter Hy Mu 80, .006" thick.

Calculations on polygon and rotor windage load showed that approximately 12 watts of power would be dissipated in windage at sea level. Calculations also showed an 8 watt power loss in bearing friction at maximum operating speed. The scan motor design is based on the calculated 20 watt bearing and windage load with provision for a contingency addition of 20 watts.

Past experience indicates that 38% cobalt steel is an optimum material for the shaft. It combines excellent magnetic properties with high strength while still permitting reasonably good machinability.

Experimental evaluation in the bearing tests indicated that the mechanical power which the motor must develop at maximum operating speed may be taken as 20 watts. An additional allowance of 20 watts is made for variations in bearing torque and to provide for acceleration torque. This brings the total design power to 40 watts.

Assuming a shaft diameter of .420 inches, the active shaft length may now be calculated from:

$$L_s = \frac{3.48\ P}{nd^2\ B_g H} \times 10^7 \qquad (1)$$

where:

where:	P	=	Power required (watts)
	n	=	Operating Speed (RPS)
	Bg	=	Max. Flux density in gap. (gauss)
	H	=	Field Density from armature Reaction (oersteads)
	d	=	Rotor Diameter (cm)
	L_s	=	Active shaft length (cm)

NOTES:

1. **SHAFT:**

1a) Grade, "Simonds" Designation: #3500-37% Co.

1b) Rockwell C Hardness: 60 - 65 Hardened

1c) Hardening Temperature: 1725°F

1d) Time at Temperature: 10 - 15 minutes

1e) Quench: Oil, well agitated (110 - 125°F)

1f) Head chrome plate shaft per detail "B": Plating to be .004 to .006 thick on finished bearing journals and thrust surfaces. Plating must extend to centers as shown.

2. **POLYGON MIRROR:**

2a) Material: Aluminum alloy

2b) Facets: Sixteen, equally spaced

2c) Face Variation: Total azimuth 6 arc/sec.; total pyramidal 10 arc/sec., ±5 arc/sec. to center line -A-

2d) Face Edge Roll Off: .012 Max. at Polygon Face intersections and edges

2e) Face Flatness: Flat to $\lambda/8$

2f) Face Finish: 20/10

2g) Face Reflectivity: 90 - 92%, Total variation 0.5%

SHAFT - POLYGON ASSY.

3a) Nickel-Cobalt plate 10 - 20 μ in. thick, 8 - 10 finish, coercivity 400 - 600 Oersted

3b) Shaft-Polygon Assy. to maintain integrity to 1200 R.P.S. ultimate speed

3c) Assy. Balance: 200 μ oz. inches.

3d) Final dynamic balance to be performed in Ampex furnished motor shaft assy. (with electronic drive equipment) to a design goal of total pyramidal error of ± 3 arc. sec. between 500 - 820 R.P.S.

Figure 15 Horizontal Scanner Notes & Tolerance

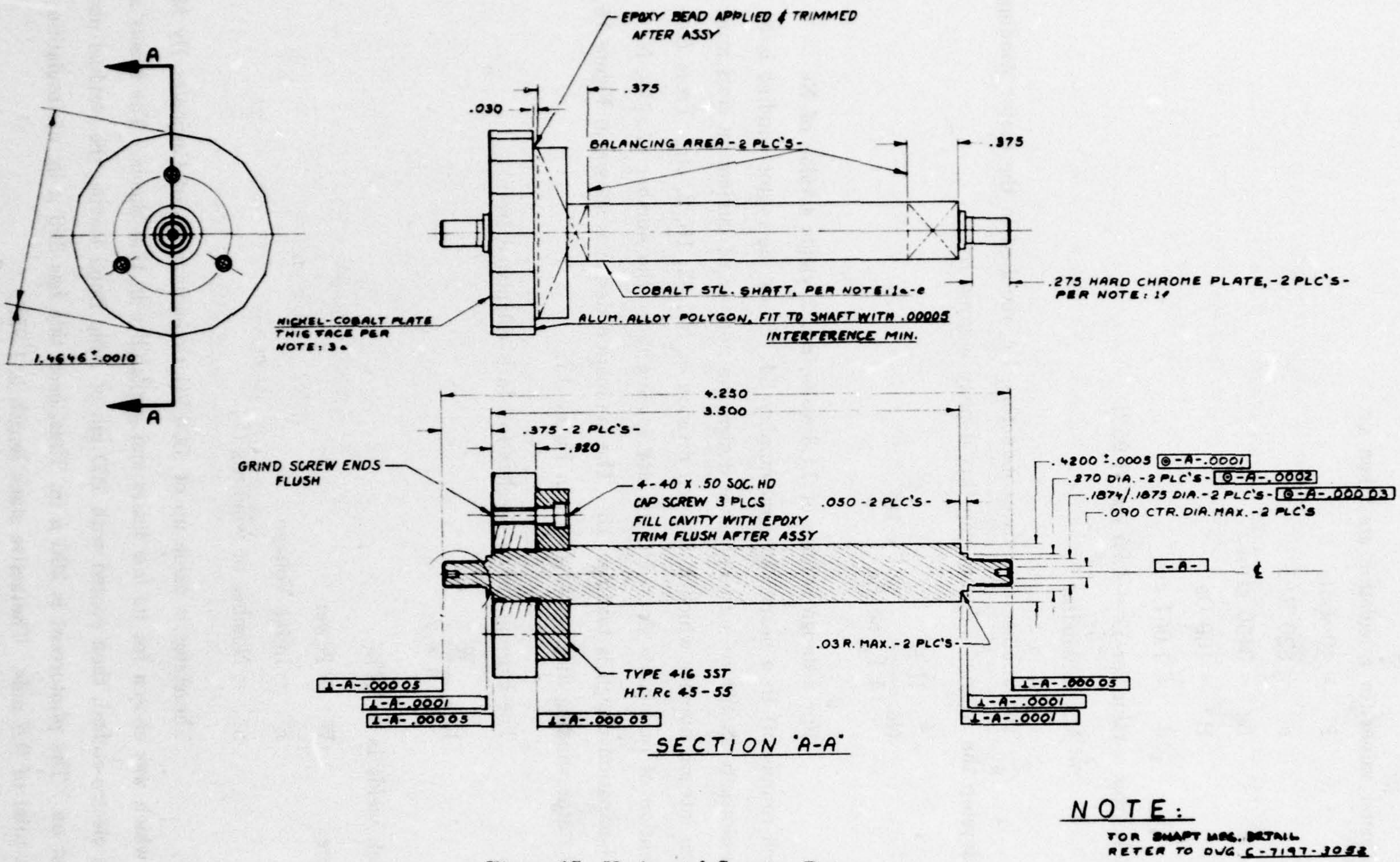


Figure 15 Horizontal Scanner Rotor

Parameter values for calculation are taken as:

$P = 40$ watts

$n = 820$ RPS

$Bg = 3450$ gauss

$H = 100$ Oe

$d = 1{,}067$ cm

which gives a value for $Ls = 4.95$ cm (1.95")

Motor Winding

The number of active conductors, Nc, required in the motor winding to develop the selected value of gap flux density is given by:

$$Nc \quad \frac{\text{II } E}{4\ L_s\ nd\ Bg} \times 10^8 \tag{2}$$

For a design voltage of 11.3 volts, Eq. 2 yields a value of Nc which rounds off to a nearest integral number 64. Since the motor winding is to be essentially similar to a two-phase ac design, the number of lamination slots must be an integral number which is an even division of Nc, 32, 16, 8, etc. From consideration of reasonable slot width to slot spacing ratio, the number of slots, N, for lamination design is taken as 16. The lamination design is shown in Figure 16. The stator winding diagram is shown in Figure 17.

The current during acceleration Ia is calculated from:

$$Ia = \frac{W}{n \times e} \tag{3}$$

which yields Ia = 1.77a

where: W = Power

E = Input Voltage

n = Number of windings (2)

The stator is made up of .006" thick laminations of Carpenter Hy Mu 80 which was chosen for its low losses and availability in thin sheets. The sheets are first electro-etched, then coated with 100 μin of Able Bond leaving the residual photoresist on. The photoresist is 200 μ in. Thus, each side has 300 μ in. of insulation or a total of 0.6 mils. The active stack length is 1.95".

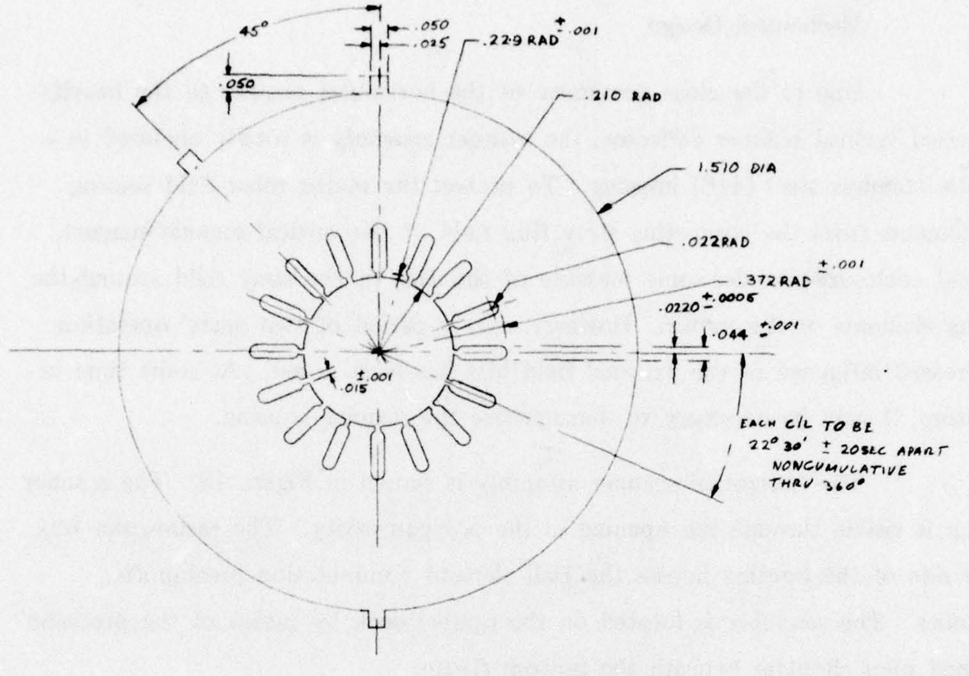


Figure 16 Motor Lamination

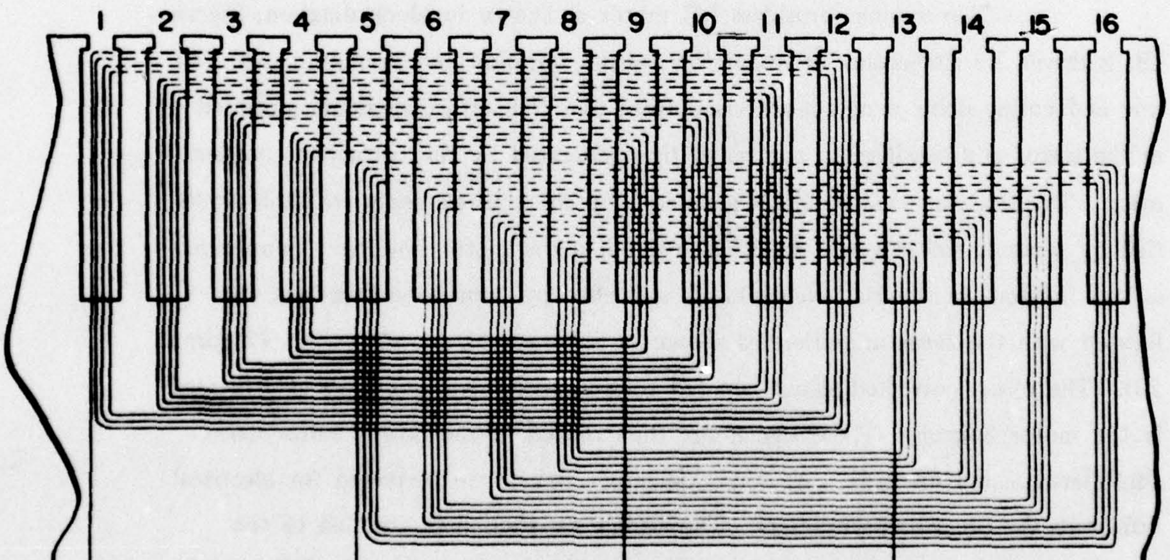


Figure 17 Stator Winding Diagram

3.2.5 Mechanical Design

Due to the close proximity of the horizontal scanner to the heavily magnetized vertical scanner deflector, the scanner assembly is totally enclosed in a magnetic stainless steel (416) housing. To protect the motor rotor field sensing Hall elements from the competing stray flux field of the vertical scanner magnet, the total enclosure provides some measure of shunting of the stray field around the working elements of the motor. However, over a period of two years' operation, an increased influence of the external field bias has been noted. At some time in the future, it may be necessary to demagnetize the scanner housing.

The horizontal scanner assembly is shown in Figure 18. The scanner polygon is visible through the opening in the polygon cavity. The rectangular box on the side of the housing houses the Hall element commutation preamplifier electronics. The assembly is located on the optical deck by means of the precision machined pilot shoulder beneath the bottom flange.

3.2.6 Motor Driver

The scanner brushless DC motor as shown in block diagram, Figure 19, is driven by sine-cosine drive for low torque variation and minimum loss. The sine and cosine drive signals are derived from two Hall effect elements mounted in the stator and sensitive to the radial flux generated by the permanent magnet rotor. The sine and cosine signals generated by the Hall elements are then amplified by separate linear sense amplifiers located in the motor housing. Geometric offsets inherent in the Hall elements are cancelled by trim potentiometers also located with the sense amplifiers as shown in Schematic Dwg. 7197-2001 (Figure 20). The offset corrected signals are fed to a pair of drive amplifiers also located in the motor housing. These signals are then routed to the power motor drive amplifiers located on AM1. At AM1, the input signals are corrected for electrical offsets in the preceding amplifiers. The signals are then A.C. coupled to the motor drive power amplifiers. DC coupling is also provided through FET switches bypassing the capacitive coupling devices for motor starting. Once the motor has obtained full operational speed, only AC coupling is used. The 741 operational

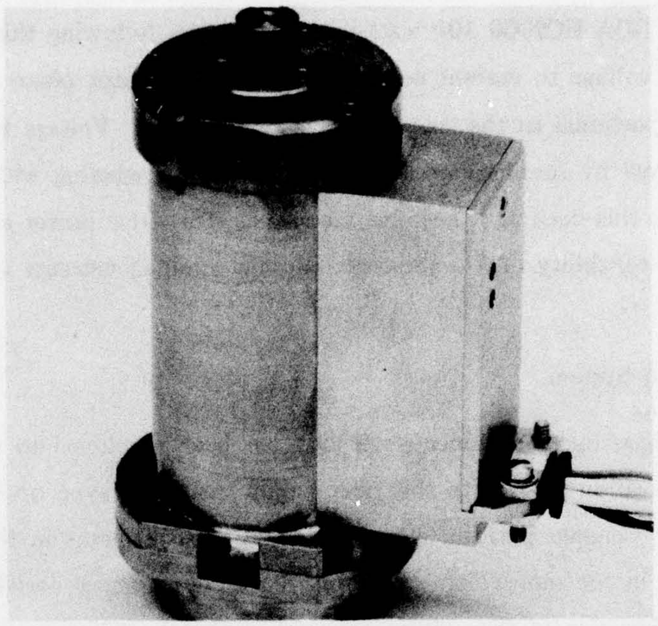


Figure 18 Horizontal Scanner Assembly

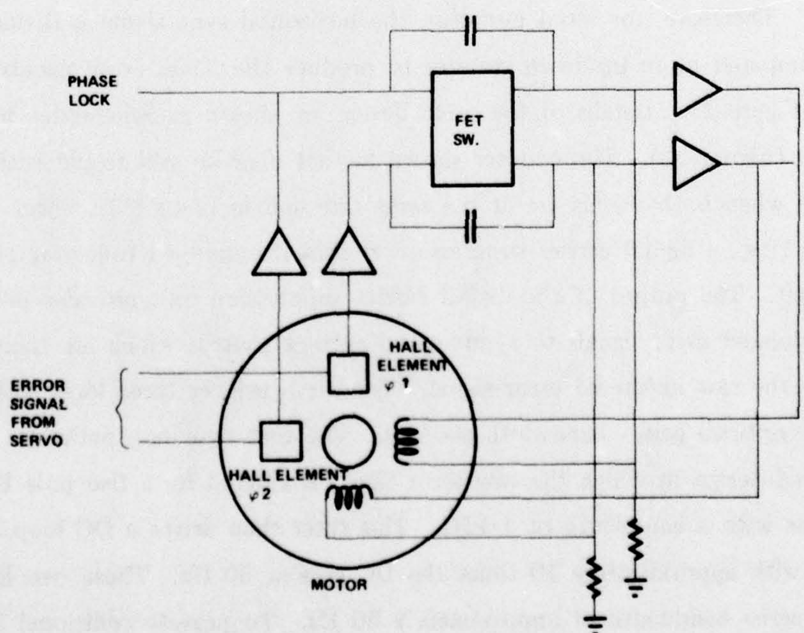


Figure 19 Motor Driver Block Diagram

amplifiers and the RCA HC2000 100 watt linear amplifiers following this coupling network provide a voltage to current conversion, thus each motor phase is driven with a current proportional to the sine or cosine input signal. Voltage to current conversion is achieved by sensing current through the motor winding with a 1 ohm resistor and feeding this back as a negative feedback. The drive power amplifier has a peak current capability of 7½ amperes. Normal running currents are typically under 1 ampere.

3.2.7 Servo System

A phase locked scanner servo loop has been employed to maintain accurate polygon position relative to the video input horizontal sync on video channel number 1. Scanner position is sensed by the Hall elements in the scan motor as described in the motor driver section. Position sensing is derived by detecting the zero crossing of the voltage on motor phase 1. This zero crossing produces a once-around tachometer signal used as the polygon phase/reference signal. This tachometer signal occurs once every 32 horizontal scan lines. It is related to the horizontal rate by the 16 polygon faces, each of which produce two scan lines. Therefore, for servo purposes, the horizontal sync signal is divided by 32 and compared in an up/down counter to produce the phase error signals as shown in Figure 21. Details of the servo design are shown in Schematic Drawing 7197-2000 (Figure 22). The counter shown in that diagram will toggle with a 50% duty cycle when both signals are at the same rate and in phase. To reject the resulting carrier, a digital carrier suppression system is employed following the counter unit. The output of the digital carrier suppression unit provides pulse width modulated drive signals to symmetrical current sources which are then summed to provide the raw unfiltered error signal. The servo utilizes three loop paths to provide an optimal gain - bandwidth product. The first two loop paths are of a conventional design in which the raw error signal is filtered by a five pole Butterworth filter with a bandwidth of 1 kHz. This filter then drives a DC loop and a lead loop with approximately 10 times the DC gain at 50 Hz. These two loops provide a servo bandwidth of approximately 50 Hz. To provide additional long

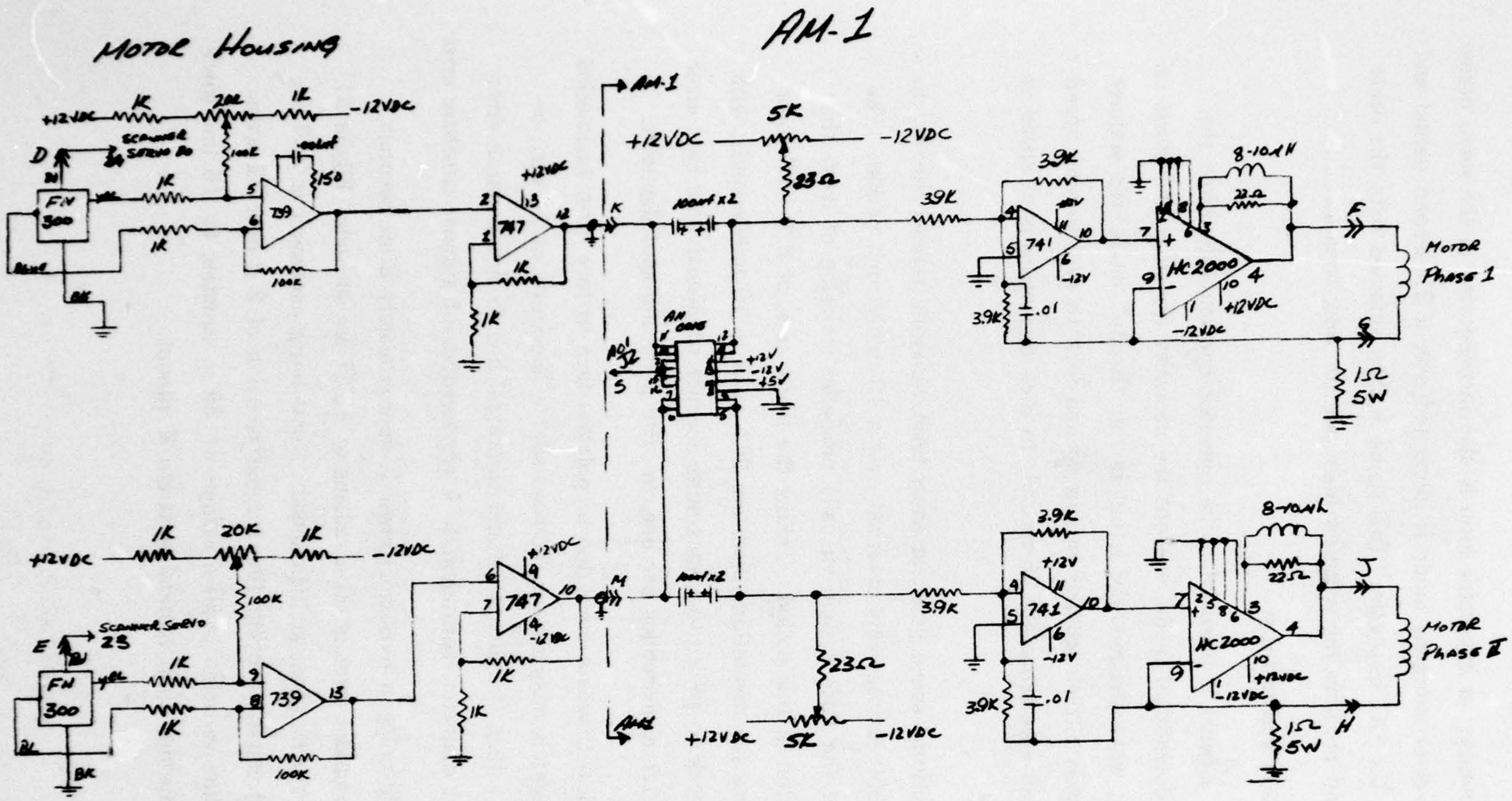


Figure 20 Motor Driver Schematic Diagram

term positional accuracy, an integrator loop is also incorporated in the servo design. The output of the error summing mode is integrated over a 2½ second period and at a gain 40 times the DC loop gain. This signal is then summed with the other two loop signals and provides the requisite high gain for long term stability.

3.2.8 System Performance

The scanner is intended to be operated continuously when the recorder is in the operational mode, without the necessity for stops and starts on demand. However, when the recorder is put in the "Ready" mode, the scanner requires approximately fifteen seconds to run up and lock to synchronous speed at 525 line rate, and approximately 25 seconds to lock to synchronous speed at the 875 line rate.

Rotational speed jitter, or short term variation, related directly to timebase error, is 150 nanoseconds observed over a 10 millisecond period. The very high inertia of the rotor system virtually precludes inclusion of more than one cycle of variation in this period. Taking the worst case, at 820 RPS rotor speed, with 32 scans per revolution, there are 263 scans in 10 milliseconds; with 150 nanoseconds peak to peak jitter, maximum scanner rotational time base error is of the order of 1.1 nanoseconds per line, or .195 μ, or .03 spot diameter.

Optical timebase error due to polygon face to face error (azimuthal error) of six arc seconds mispositions the scan spot a maximum of 12 sec., or 1.0μ anywhere on a line. Total optical and rotational line to line position error is 1.2μ, or 0.2 spot diameter, equivalent to 7 nanoseconds of scanner timebase error.

While polygon pyramidal error is approximately 8 arc seconds, total rotational pyramidal error is 60 μ radians or 12.37 arc seconds. Figure 21 shows pyramidal error detected at high speed. Total beam excursion is 24.7 arc sec (120 μ radians) causing a cyclic line spacing variation of 2 μ over 32 scans. Maximum line to line variation is 50 μ radians or .85 μ, equating to .16 line space in an 875 line frame due to pyramidal variation & runout.

3.3 Vertical Scanner

The performance criteria, design basis, and feasibility of the galvanometer driven vertical scanner was reported in Reference 1 (pp 53-82). The design was further developed and improved as reported in Reference 2 (pp 91-100). Due to the requirements of the scan optics system, described in Section 3.1.3.9, the mirror element for the VLBR was required to be larger than that of the unit developed

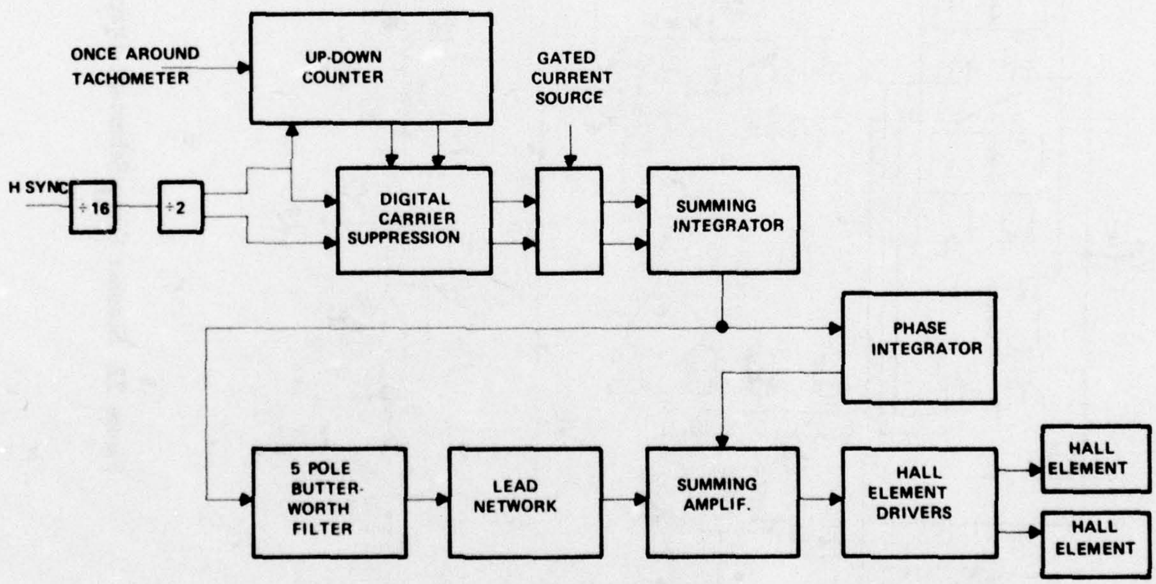


Figure 21 Scanner Servo Block Diagram

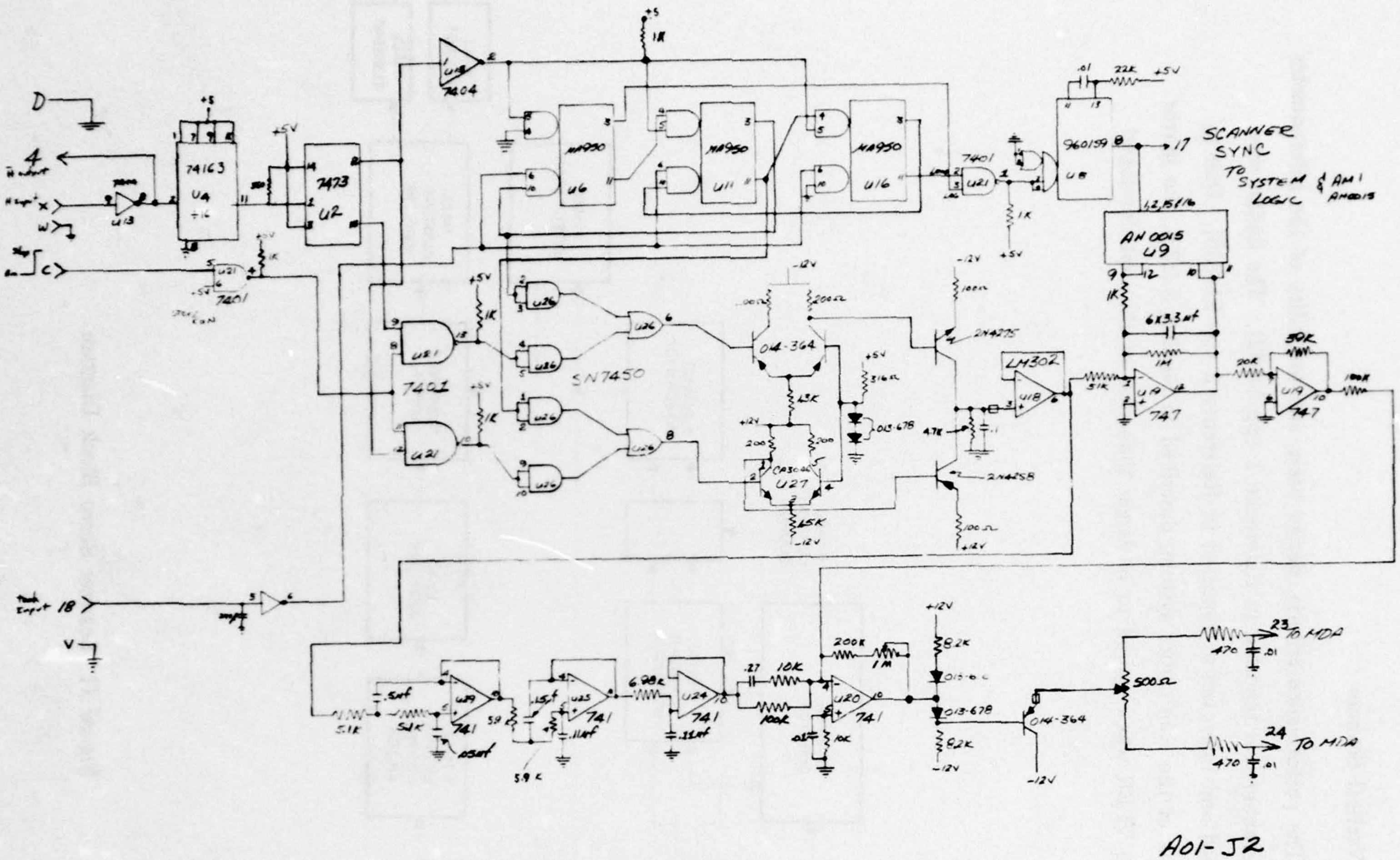


Figure 22 Scanner Servo Schematic Diagram

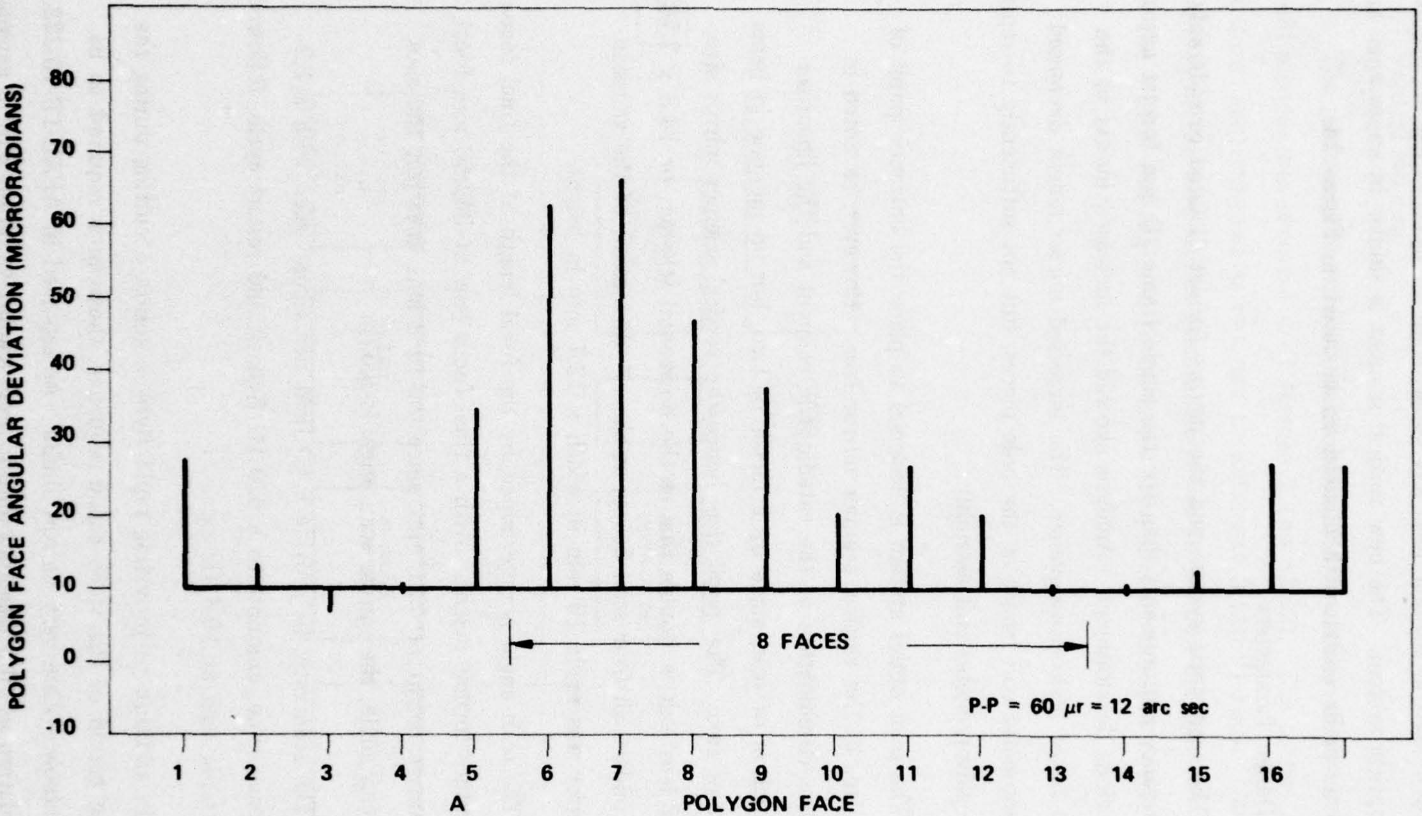


Figure 23 Scanner Pyramidal Error

previously. A new vertical scanner unit was constructed to dimensional requirements of the VLBR optical system. The new vertical scanner is similar in appearance and construction to its predecessors, with dimensions as shown in Figure 24.

3.3.1 Design Parameters

The scan optic system and the picture format dictated considerably different performance requirements than for the single frame 16 mm format accommodated in previous development. Analysis showed the increased inertia of the larger mirror to be of little consequence. The increased mirror length decreased the active galvanometer coil length at the pole pieces, but not sufficiently to require redesign of the galvanometer coil assembly.

The scan optics system is designed to place the entrance pupil of the final focus lens at the vertical scanner mirror face. However, as noted in Section 3.1.2, the combination of the catadioptric element and the linearizer results in a reduction of scan angle by a factor of two, but an increase in beam size by a factor of two. The pupil size, hence the vertical scanner mirror size, at the linearizer lens exit is double that at the horizontal scanner, or 14.8 x 7.76 mm. to accommodate all four scan beams at the e^{-4} dimension of the gaussian beam. The mirror was made 16 mm in width x 12.7 mm in height.

The scan angle is determined by the focal length of the final focus lens and the picture format height. With a final focus lens of 34.286 mm focal length and an image height of 4.21 mm, since the final lens linearizes the spot position with scan angle, the mirror scan angle is 3.52°.

The scan rate, to provide a 60 field per second scan with a 1.2 millisecond flyback time, amounts to a 620 Hz flyback and restart cycle, followed by a 15.5 ms frame scan at 19.4 Hz rate.

In addition to providing rapid flyback action occurring during the vertical blanking period of the video signal sequence, the scan is required to be linear and repeatable within very narrow limits. As reported in AFAL-TR-70-223, (pg. 57), the relation of film transmittance to line spacing variation with a gaussian spot scan is

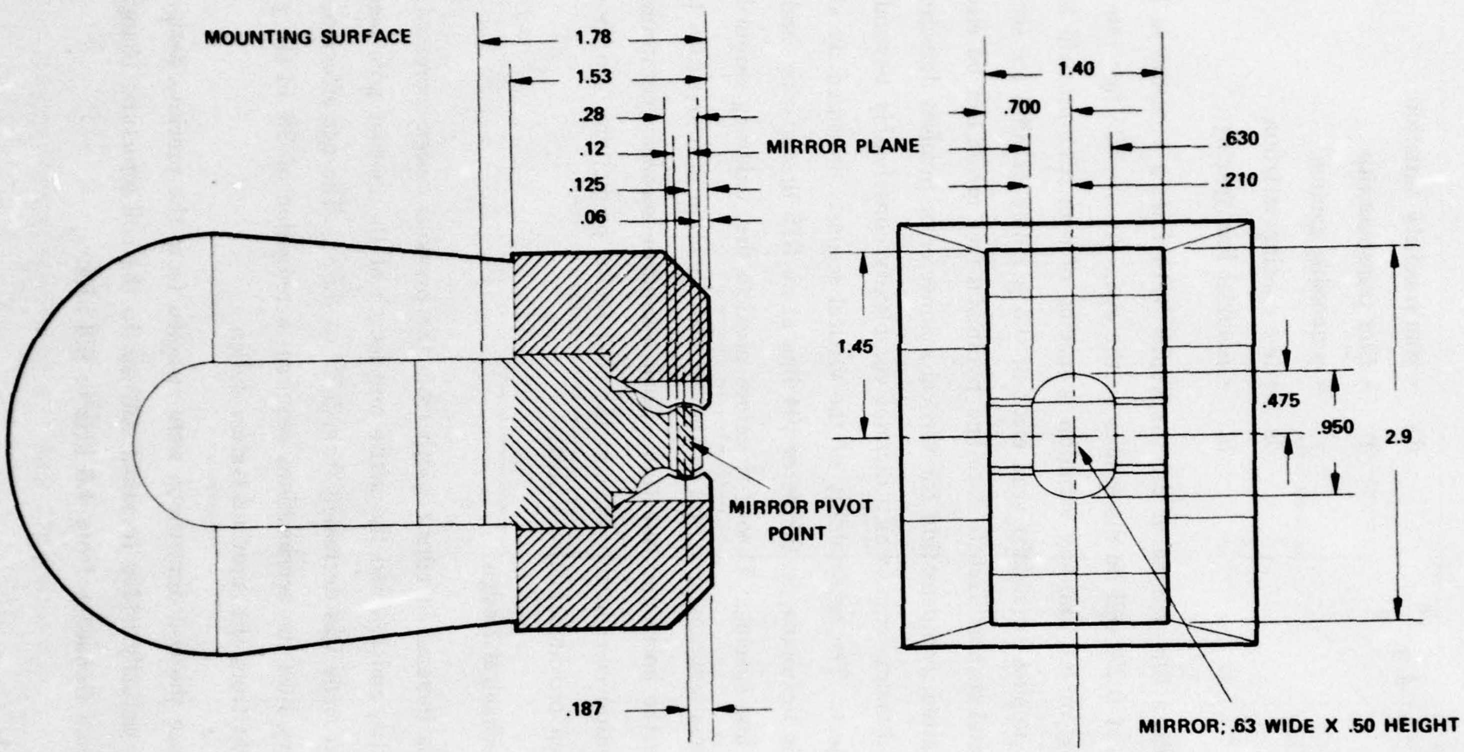


Figure 24 Vertical Scanner

$$\frac{dT}{T} = 4\gamma\frac{ds}{s}$$

dT = transmissivity variation

T = film transmissivity

γ = processing gamma

ds = line spacing variation

S = nominal line spacing

With a film gamma of 2.5 for Kodak 3414 film, a variation in line spacing in excess of 0.2% will be discernible to the eye. At the 875 line rate with a line spacing of 5.3 μm, any variation is spacing of over .011 μm will be discernible. This implies an angular scan error of 0.3 μ radian or .062 arc sec. While the horizontal scanner face to face and pyramidal face errors can be electro-optically compensated, compensation for vertical scanner error involves detecting and servoing the dynamic scan, which dictates complexity considerably beyond the scope of the project. The repeatability of the vertical scanner, measured by an r.f. interferometric technique, is .005%, or .04 line at an 875 line spacing, and .025 line at 525 line spacing. Theory therefore predicts that twinning would be clearly visible unless scanning spot size in the vertical direction is four to six times the spot width in the horizontal direction. Such a solution seriously compromises the vertical resolution considerably beyond the Kell factor prediction. No spot distortion has been provided in the VLBR.

3.3.2 Mechanical Design

The increase in mirror width from the previous design increased the rotor system inertia, and lowered the active coil length at the magnet pole pieces. However, the scan angle was decreased from 5.7^{o} to 3.52^{o}. The net effect of the changes was, to produce the accelerations required, a reduction of 3% in the galvanometer coil current from the previous system design.

Since the coil dimensions were retained from the previous design, the lengthened mirror actually added torsional stiffness to the coil structure, changing the natural torsional frequency from 4.6 kHz to 6.3 kHz.

An effort was made to reduce the natural frequency of the rotating assembly below that of the previous design. Bendix flexural pivots, Model 5004-800, produced a 53 Hz natural rotational frequency. This proved to be adequate to cope with the 19.4 Hz scan frequency and the 620 Hz flyback frequency.

3.3.3 Driver and Timing

The galvanometer driver which is shown in Figure 25 consists of a triple pulse generator locked to incoming vertical sync and a ramp generator to provide the vertical scan. A low impedance galvanometer driver is employed to provide damping for the pseudo-ballistic galvanometer. Since the galvanometer is wound with aluminum ribbon coil, and thus its resistance varies with temperature, a current sense feedback loop is employed to vary the pulse amplitudes in response to galvanometer resistance changes. Details of the circuits employed are shown in Figure 26.

Referring to the block diagram shown in Figure 25, pulse width and timing is controlled by the counter pulse generator. The counters are programmed in response to the line rate programmer to accommodate 525 line and 875 line formats. Thus, the counter is preset for each line rate to produce identical pulse widths. The counter outputs then switch between three pulse height reference sources through the FET commutator. Thus, the input to the galvanometer driver is a voltage triplet of fixed period at varying amplitude. The resulting drive waveform is shown in Figure 27. Current is sensed during the first pulse by the current sense unit and fed back to the pulse height reference sources varying their amplitude in response to variations in deflector current and, therefore, resistance. The pulse height reference source is externally controllable from the Run-Stop command and, therefore, either produces galvanometer scan or stops in response to other system commands. The function of the three pulses is as follows: the first pulse initiates galvanometer flyback; the second pulse stops the galvanometer at the extreme of its swing; the third pulse provides damping and starts the new scan. The ramp keeps the galvanometer running at the proper speed during vertical scan.

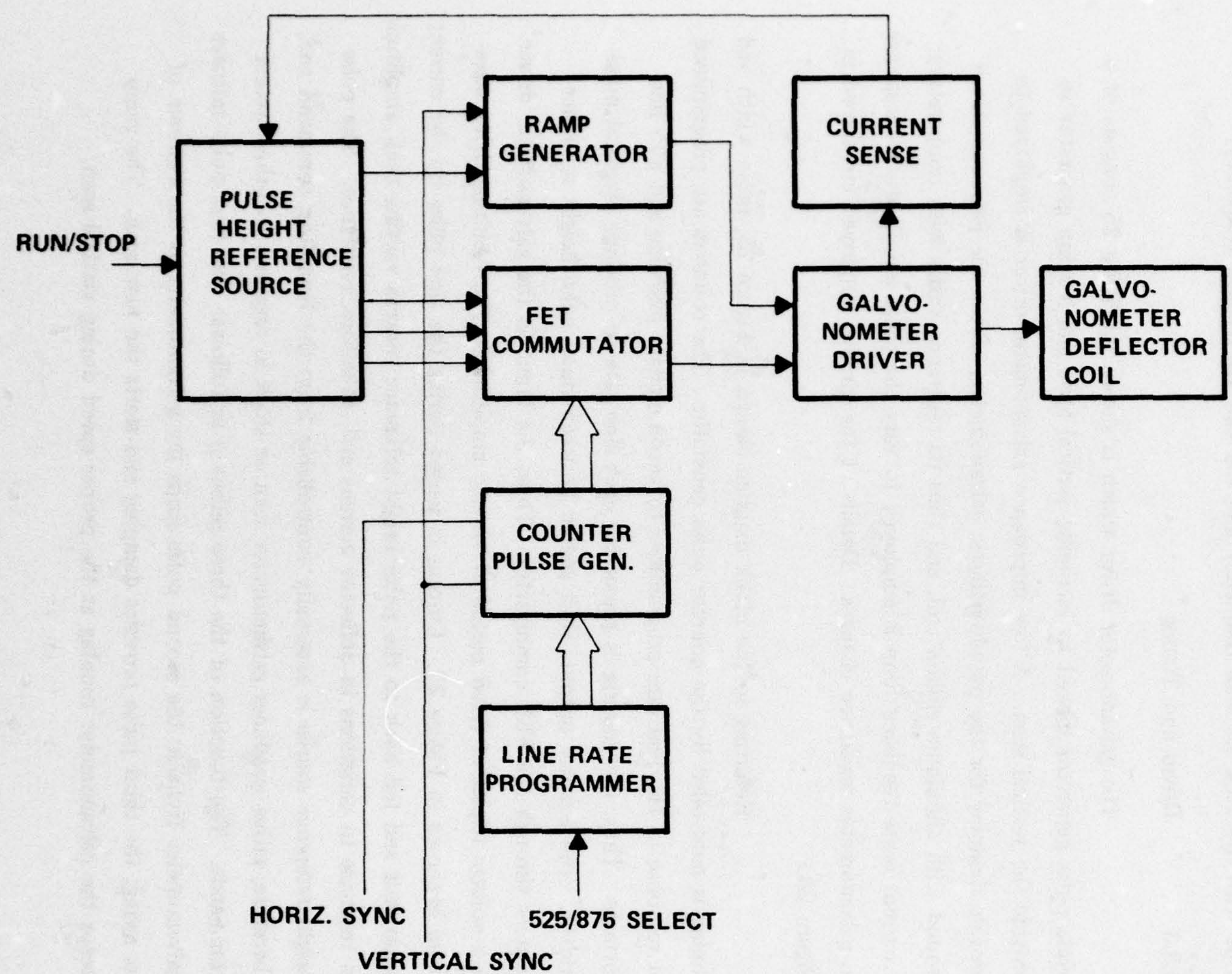


Figure 25 Vertical Scanner Control & Driver

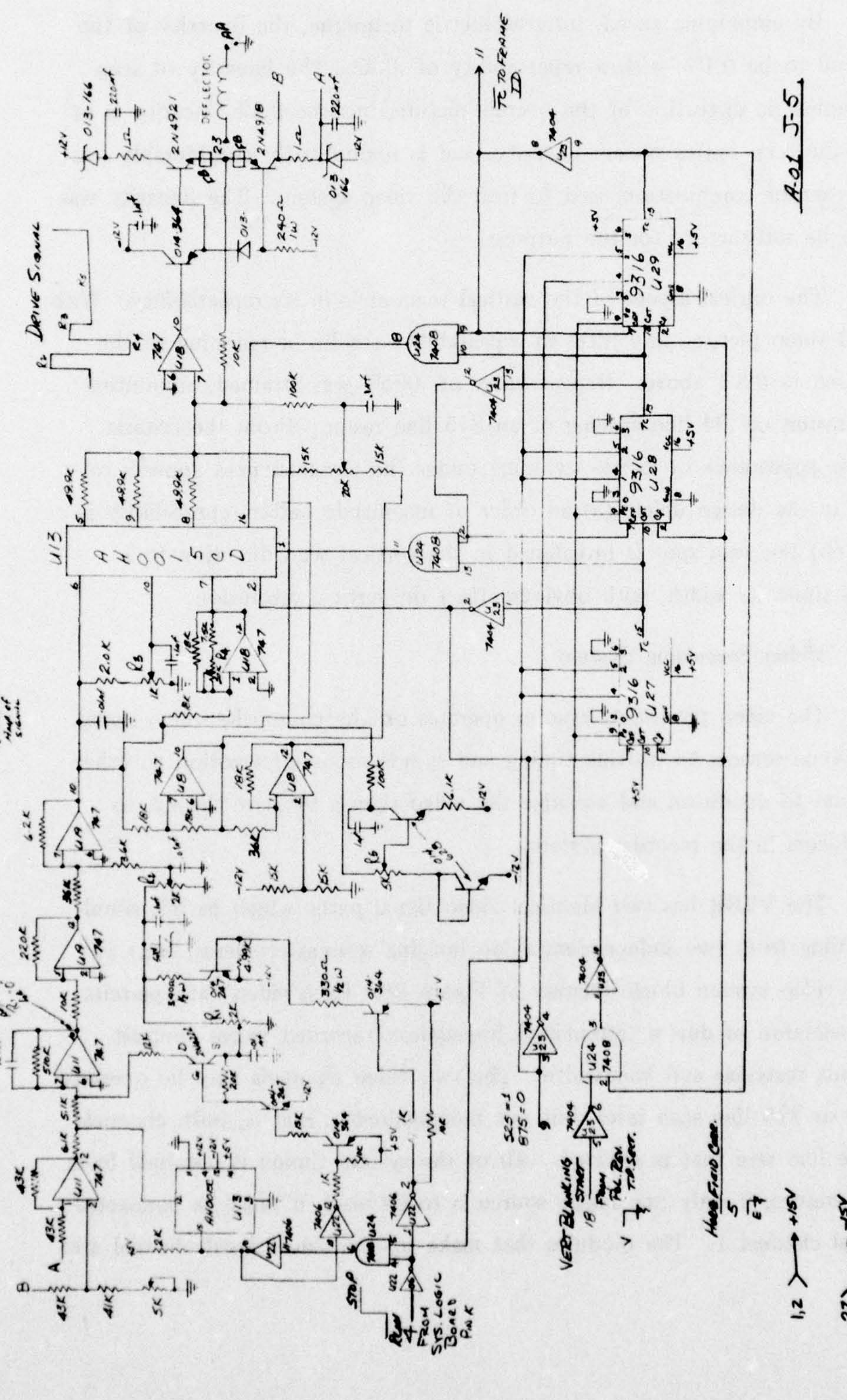


Figure 26 Vertical Scanner Control Schematic Diagram

3.3.4 Performance

By employing an r.f. interferometric technique, the linearity of the scan was found to be 0.1%, with a repeatability of .005%. The linearity of scan affects the geometric distortion of the overall picture, but the 0.1% linearity is of the order of the scan optics system linearity, and is undoubtedly considerably less than any lens-sensor combination used to feed the video system. The linearity was considered to be satisfactory for the purpose.

The critical aspect of the vertical scanner is in its repeatability. With the interlaced video picture, any jitter in repeatability results in twinning to the extent discussed in 3.3.1 above. Repeatability of .005% was attained, amounting to .025 line raster, or .04 line spacing of an 875 line raster. From the criteria developed, the appearance of visible twinning under the circumstances appears to be inevitable in the design unless (a) an order of magnitude better repeatability is attained and (b) the scan spot is broadened in the vertical scan direction to a height several times its width, with obvious effect on vertical resolution.

3.4 Video Processing System

The video processing system operates on the composite video signal from the TV-type sensors to provide timing and synchronous information to other subsystems, and to condition and equalize the video signals to drive the r.f. to optical transducers in the recorder system.

The VLBR has two identical video signal paths which permit simultaneous recording from two independent video imaging sources (cameras, etc.) as shown in the video system block diagram of Figure 28. Each video path permits independent selection of device terminating impedance, recorded image contrast polarity, gamma response and bandwidth. The two video channels may be operated at either 525 or 875 line scan rates, but not independently; that is, both channels operate at the line rate that is selected. All of the system timing is obtained from channel 1, therefore, if only one image source is to be used, it must be connected to video signal channel 1. The modules that make up the video signal channel are:

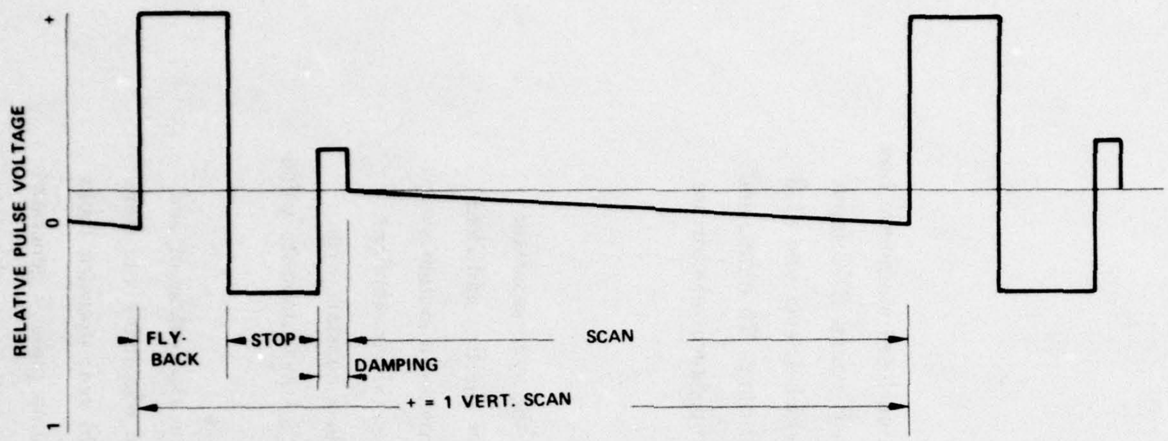


Figure 27 Vertical Scanner Driver Waveform

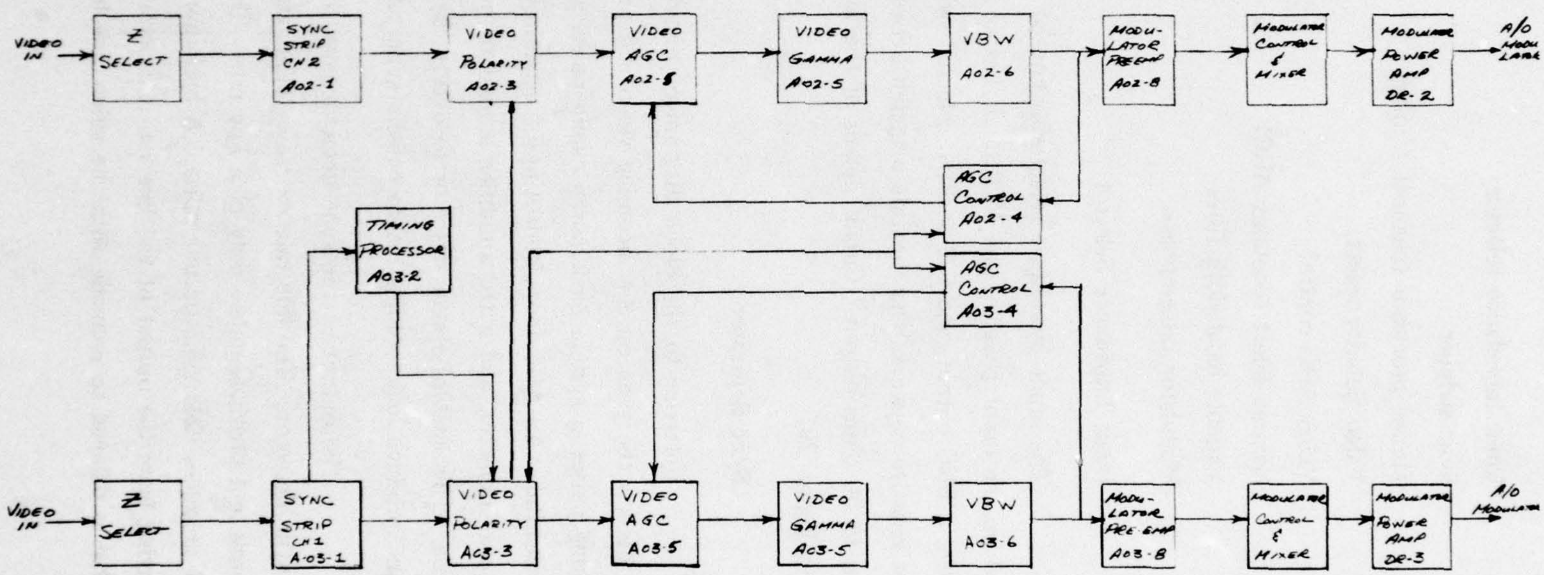


Figure 28 Video System Block Diagram

Input impedance selector
Sync stripper
Timing processor (channel 1 only)
Video polarity select
Video AGC control
Gamma select (contains AGC)
Variable bandwidth filter
Modulator pre-emphasis

3.4.1 Input Impedance Selector

The input impedance selector is housed in an enclosed aluminum box mounted on the input panel of the VLBR. It has an isolated ground BNC input receptacle, a BNC output, and a 3-position selector switch which selects one of 3 different resistive networks that provide a match between 50 ohms, 75 ohms, and 93 ohms to 50 ohms output. Circuit details of the input impedance selector are shown in Figure 29.

3.4.2 Sync Separator

Referring to the block diagram of Figure 30, the sync separator module detects the sync on the incoming video and produces the line and field rate timing pulses, a system back porch clamp pulse, and provides a system sync lock indication. An AGC loop, consisting of a controlled gain video amplifier, a sync peak detector, and a DC amplifier is used to maintain a constant sync amplitude. This enables a sync detector to detect the sync in the composite video signal and produce logic compatible composite sync pulses.

The output of the sync detector goes to a line rate extractor and a field sync detector. The line rate extractor eliminates odd equalizing and serration pulses and provides pulses only at a line rate. The field sync detector looks for and produces field sync output pulse. A back porch clamp pulse is generated by delaying from the output of the line rate extractor and generating a clamping pulse that is delayed to coincide with the video line back porch.

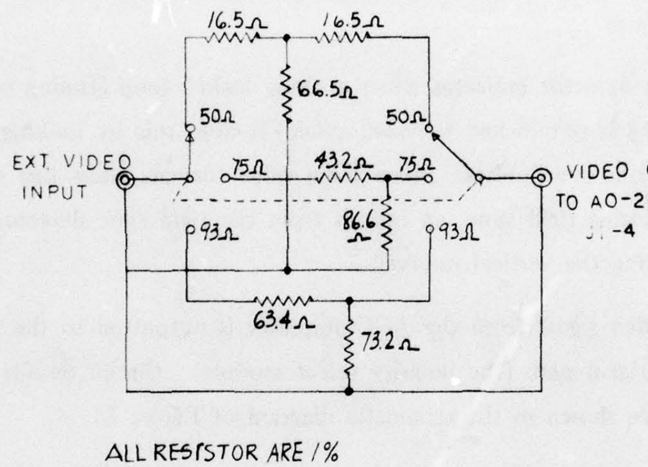


Figure 29 Input Impedance Selector

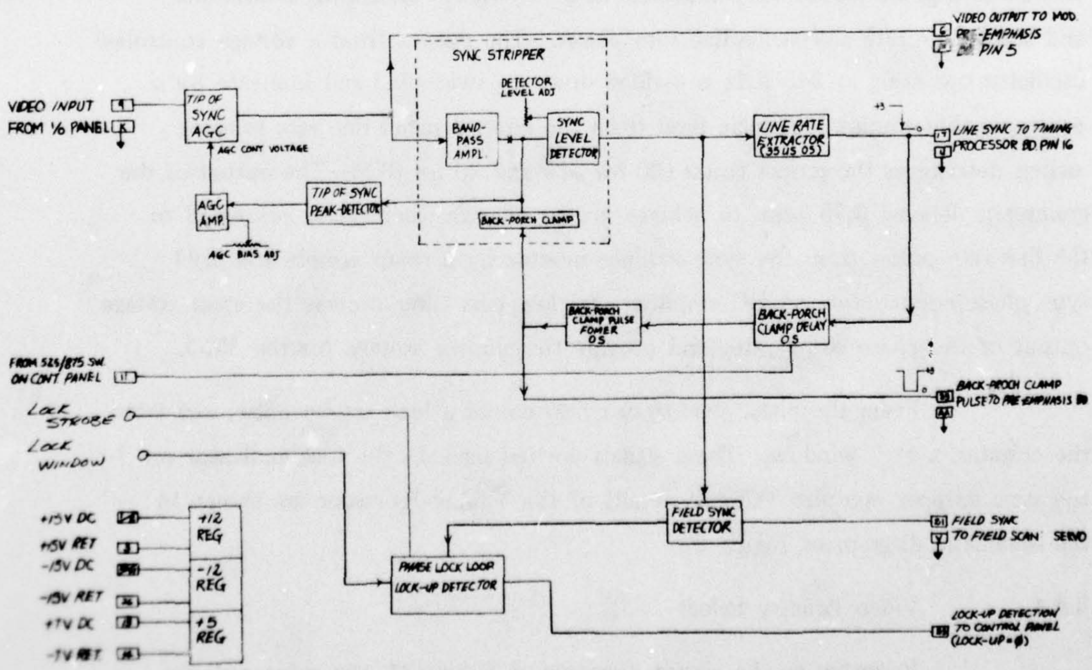


Figure 30 Sync Separation Block Diagram

The delay required is different for the two line standards (525 and 875) so a logic input from the internal control panel line rate selector switch is used to change the delay.

A lock detector indicates when a phase locked loop (timing processor) used for system timing is not locked to video sync. It does this by looking for missing or mis-timed line sync pulses. Since some video formats allow line sync pulses to be absent during field sync, an output from the field sync detector blanks the lock detector during the vertical interval.

The video signal from the AGC amplifier is outputted to the next module in the video signal path (the polarity select module). Circuit details of the Sync Separator are shown in the schematic diagram of Figure 31.

3.4.3 Timing Processor

Referring to the Timing Processor block diagram of Figure 32, the module is a phase locked loop that acts as a "flywheel" generating continuous and stable line rate and twice line rate pulses. The output from a voltage controlled oscillator operating at 945 kHz is divided down to twice line and line rate by a programmable counter. A logic level from the control panel line rate selector switch determines the proper count (60 for 525 and 36 for 875). The output of the counter is delayed 3.75 μsec. to achieve proper phasing, then phase compared to the line rate pulses from the sync stripper module by a ramp sample and hold type phase comparator. A DC amplifier and low pass filter process the error voltage output of the phase comparator and provide the control voltage for the VCO.

From the phase comparator also comes a lock strobe pulse, and from the counter, a lock window. These signals are fed back to the lock indicator on the sync stripper modules. Circuit details of the Timing Processor are shown in the schematic diagram of Figure 33.

3.4.4 Video Polarity Select

Referring to the circuit diagrams of Figure 34, the video polarity select chassis makes possible the selection of either positive white or positive black

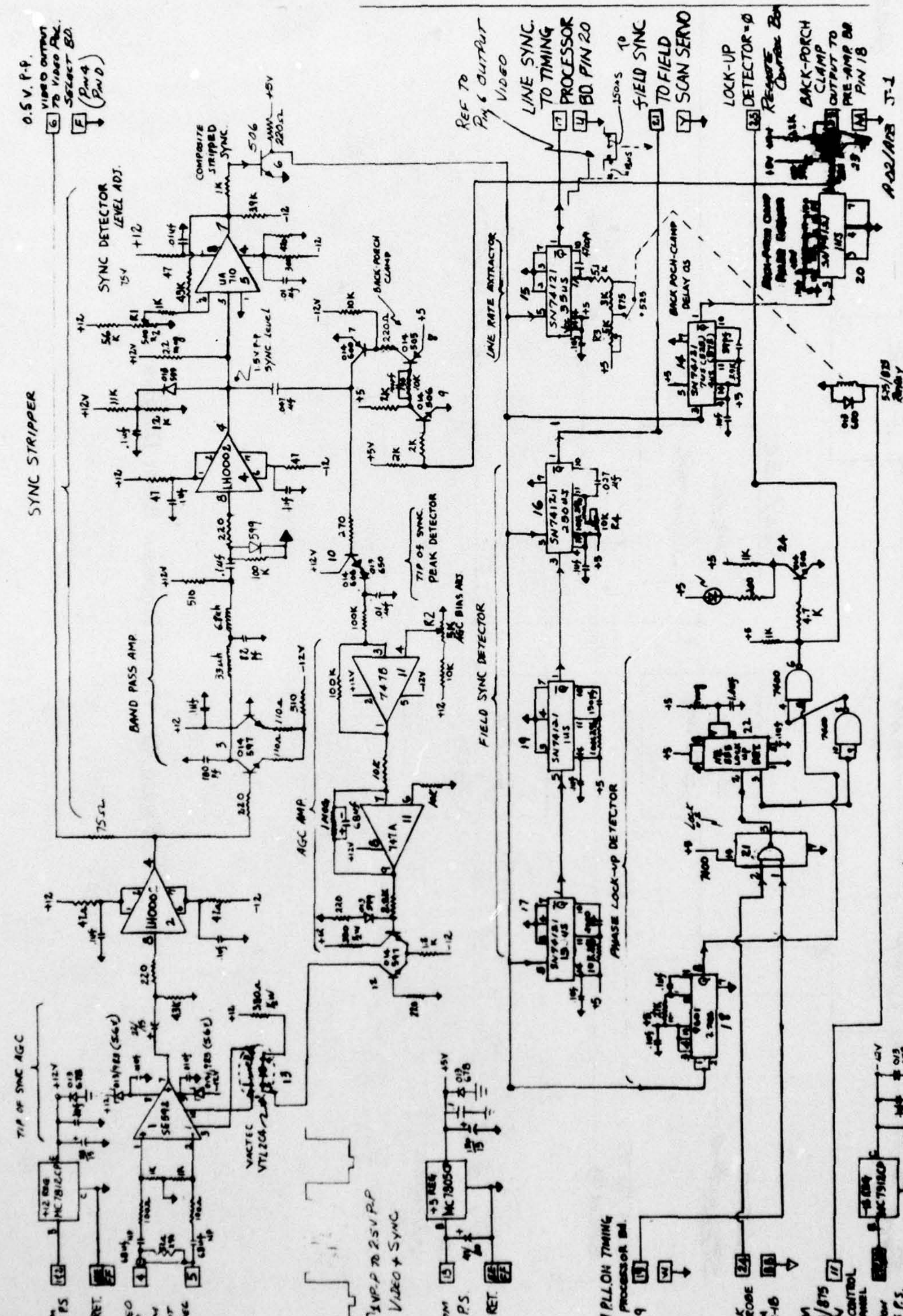


Figure 31 Sync Separator Schematic

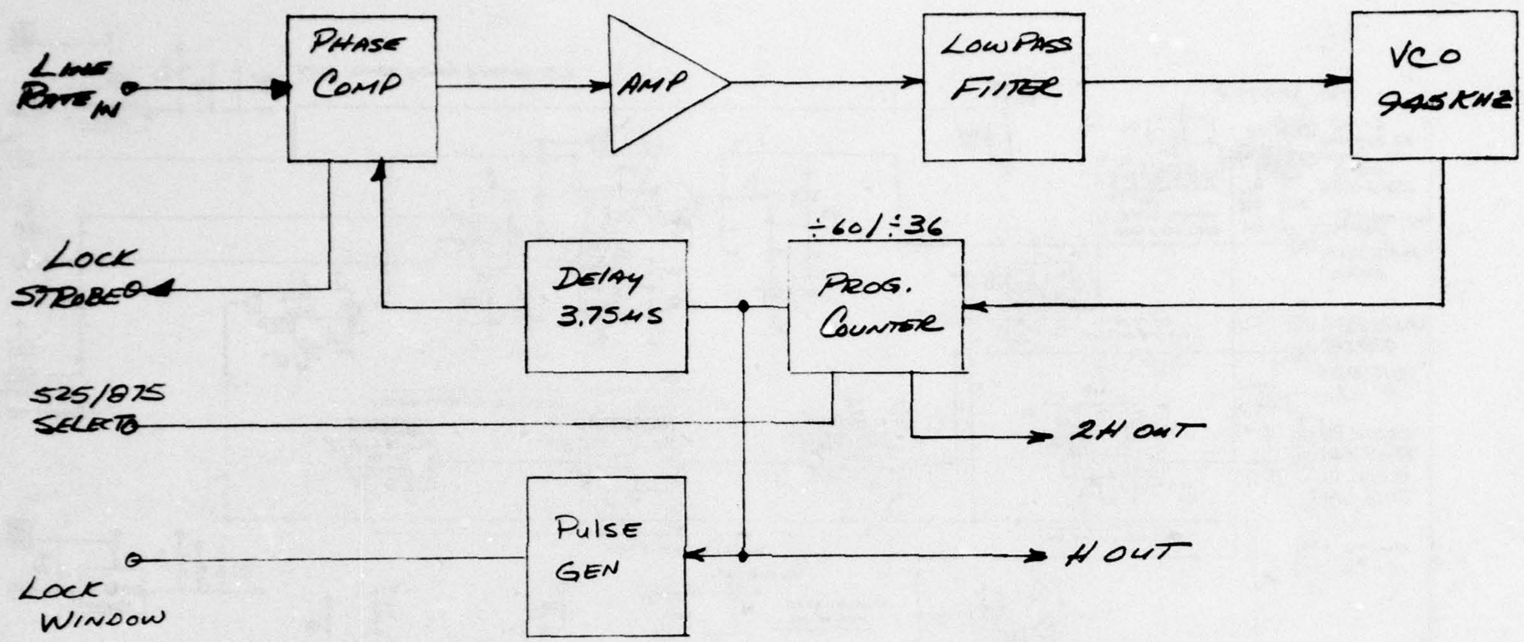


Figure 32 Timing Processor Block Diagram

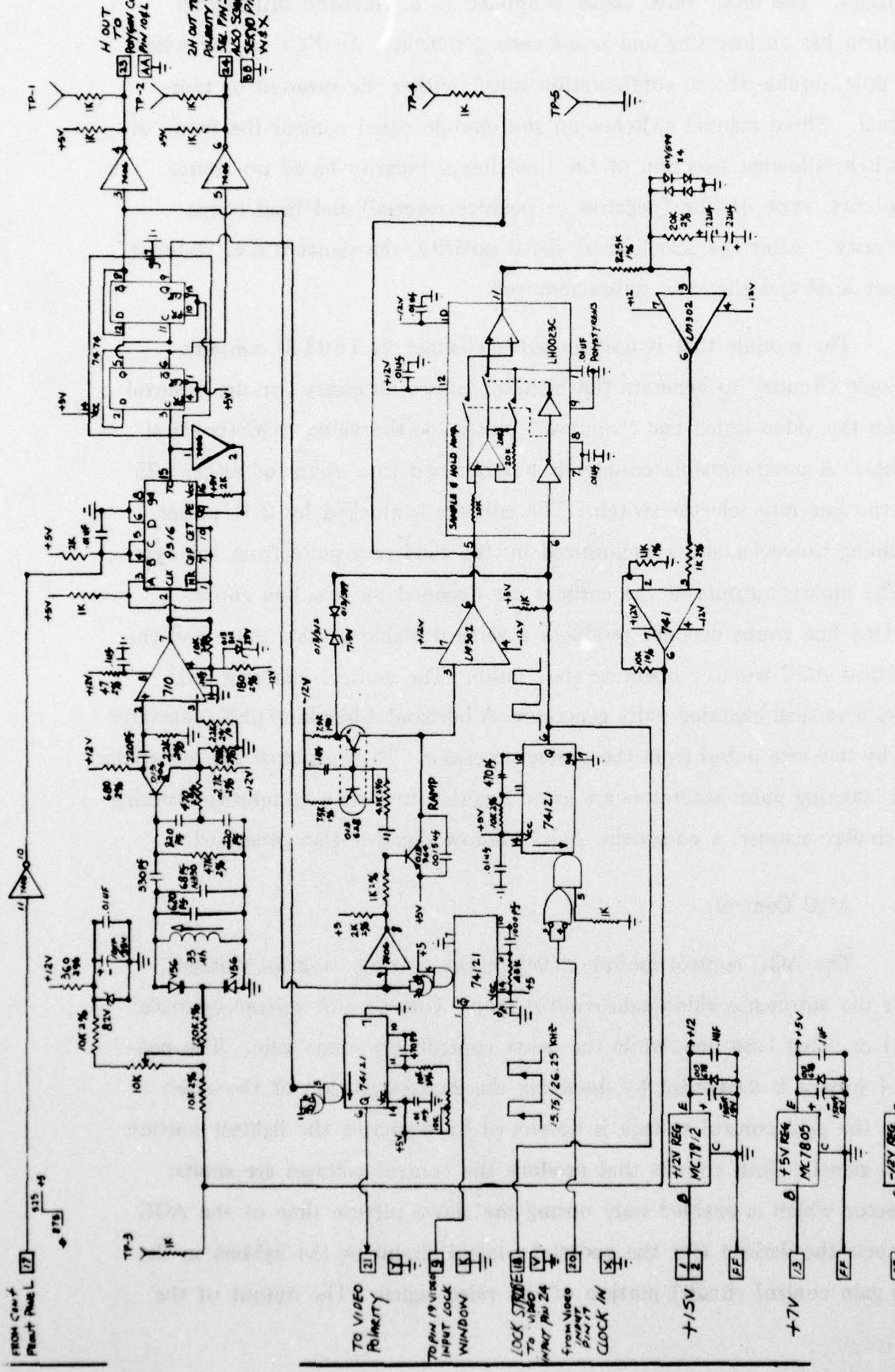


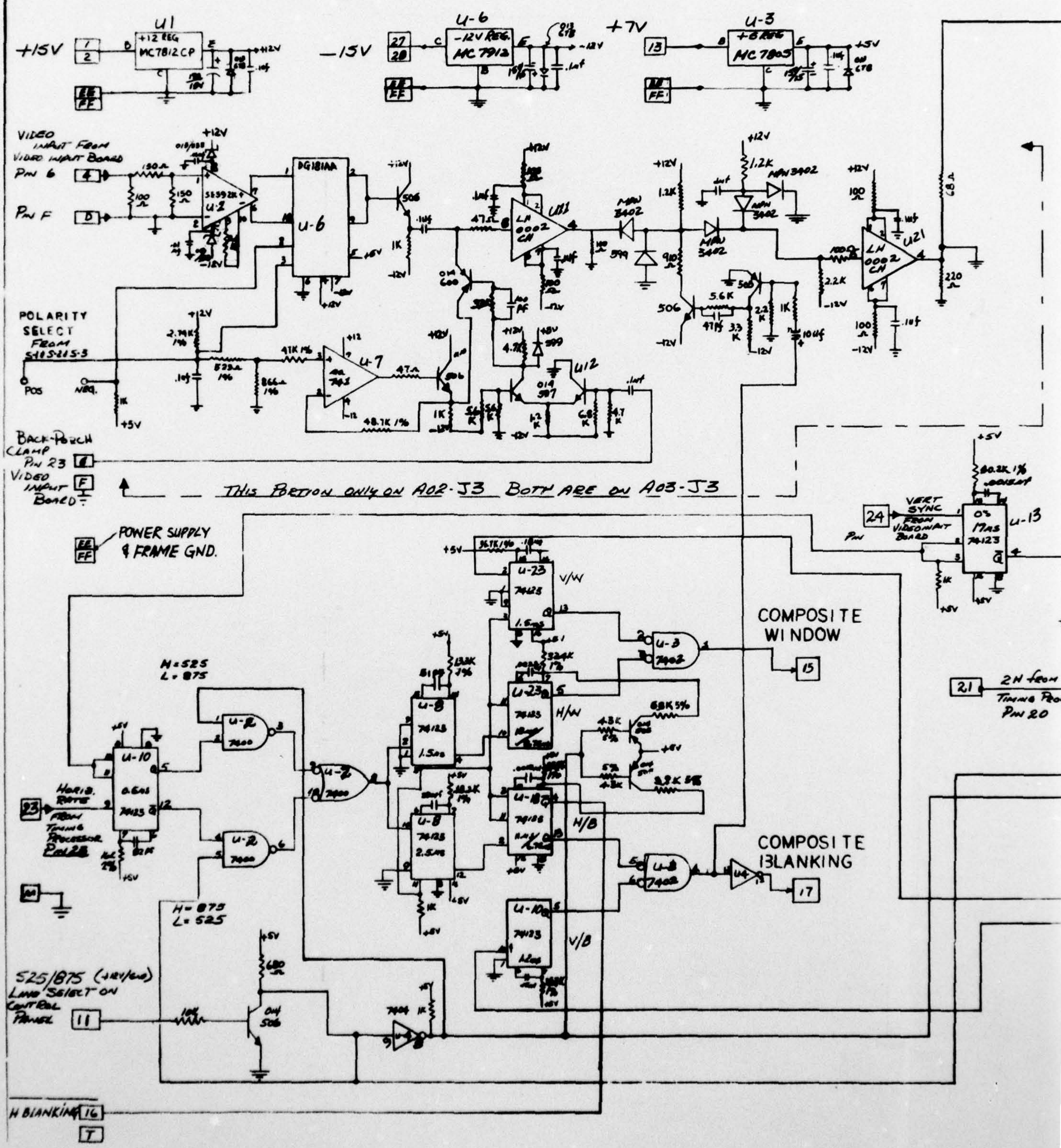
Figure 33 Timing Processor Circuit Diagram

recorded images. The input video signal is applied to a wideband differential amplifier which has an inverting and non-inverting output. An FET switch wired in a single pole, double throw configuration selects either the inverted or non-inverted signal. Three manual switches on the module panel control the mode of the FET switch, allowing selection of the final image polarity based on source (camera) polarity, type of film (negative or positive reversal) and final image contrast polarity. After the selection of signal polarity, the signal is d.c. restored to the proper level and the sync pulses removed.

The module that is used in video channel #1 (A03-3) contains additional logic circuitry to generate the blanking pulses necessary for the removal of sync from the video signal and "window" pulses for the video AGC (contrast enhancement). A programmable counter is programmed to a count of either 525 or 875 by the line rate selector switch. The counter is clocked by 2 H pulses from the timing processor and synchronized by the field rate pulse from the sync stripper. The binary outputs of the counter are decoded by two line count decoders. One line count decoder produces a vertical blanking start pulse and the other, a vertical AGC window blanking start pulse. The vertical blanking start pulse triggers a vertical blanking pulse generator. A horizontal blanking pulse generator is triggered by line rate pulses from the timing processor. The output of the horizontal and vertical blanking pulse generators are gated together to form a composite blanking signal. In similar manner, a composite AGC window signal is also generated.

3.4.5 AGC Control

The AGC control module develops the two d.c. control voltages required for the automatic video gain control loop. One control voltage controls the pedestal or video base line, while the other controls the video gain. The pedestal control voltage is developed by detecting the darkest portion of the video signal, while the gain control voltage is developed by detecting the lightest portion of the video signal. Both circuits that produce the control voltages are similar a peak detector which is enabled only during the active picture time of the AGC window detects the darkest (for the pedestal control circuit or the lightest in the case of the gain control circuit) portion of the video signal. The output of the



+15V
U1
+12 REG
MC7812CP
-15V
U-6
-12V REG.
MC7912
+7V
U-3
MC7805
VIDEO INPUT FROM VIDEO INPUT BOARD
PIN 6
PIN F
DG181AA
U-6
LH 0002 CH
U21
POLARITY SELECT FROM S105-215-3
POS
NEG.
U-7
U12
BACK-PORCH CLAMP PIN 23
VIDEO INPUT BOARD
THIS PORTION ONLY ON A02-J3 BOTH ARE ON A03-J3
POWER SUPPLY & FRAME GND.
VERT SYNC FROM VIDEO INPUT BOARD
U-13
74123
COMPOSITE WINDOW
U-23
V/W
H/W
H/B
V/B
H=525
L=875
U-10
HORIZ. RATE FROM TIMING PROCESSOR PIN 28
H=875
L=525
COMPOSITE BLANKING
2H FROM TIMING PROC PIN 20
525/875 (+12V/GND) LINE SELECT ON CONTROL PANEL
H BLANKING

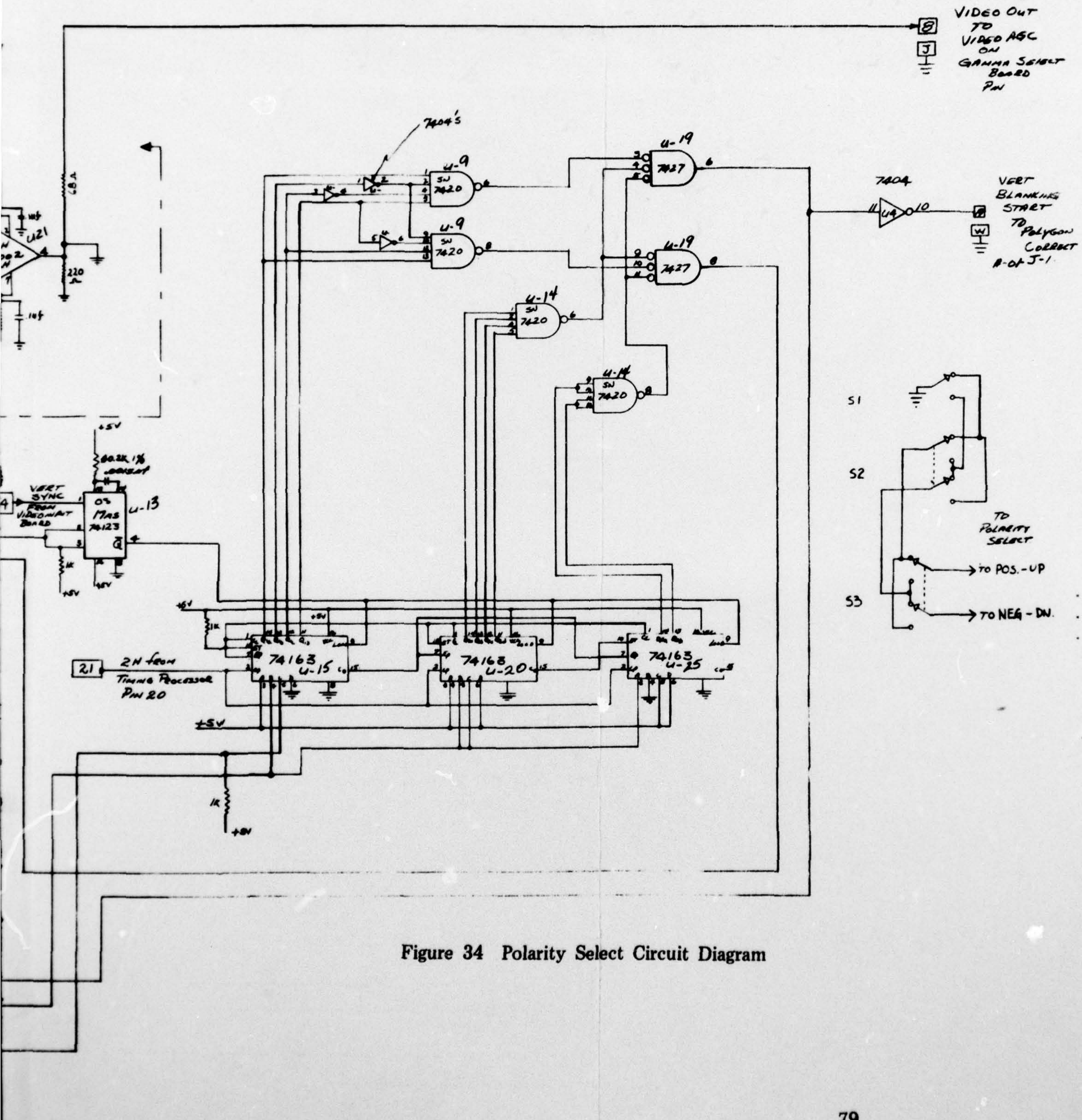


Figure 34 Polarity Select Circuit Diagram

peak detector is compared to a fixed reference and the resulting error if any is amplified. At the end of the field scan this error is stored by an integrating sample and hold circuit and the charge on the peak detector is dumped readying it for the next field. The output of the sample and hold circuit is the control voltage for that function (pedestal or gain control). Two switches are provided to allow manual settings of pedestal and gain. Circuit details of the AGC control (chassis AO2-4 and AO3-4) are shown in Figure 35.

3.4.6 Gamma Select

Referring to the gamma select block diagram of Figure 36, the module provides a selection of five gamma characteristics, a gamma corrector to extend the film density range, the video pedestal control amplifier and the video gain control amplifier. A direct-coupled video amplifier, a d.c. control amplifier and a blanking gate make up the pedestal control circuitry.

A buffered output from the blanking gate is taken to the AGC control module for detection of the darkest signal level. The control or error voltage produced by the AGC control module modifies the bias of the direct-coupled video amplifier to bring the darkest video level to zero volts. The blanking gate removes the old pedestal and establishes the video base line at zero volts. The video signal from the output of the blanking gate now goes to an electronically controlled variable gain amplifier. The control voltage for this amplifier is the gain control voltage from the AGC control module. The video signal output from the variable gain amplifier now goes to the gamma select circuitry. To achieve a selectable range of gammas, the video signal is passed simultaneously through a logarithmic amplifier and a linear amplifier. The outputs of these two amplifiers are then mixed and the mixing ratio is selected by the gamma select switch.

The logarithmic amplifier is set to have a gamma of 1.50 ($Eo = KEi^r$). The gamma select switch allows the selection of gammas equal to .8, .9, 1.0, 1.1, and 1.2 of normal film gamma. The video signal is now passed through another gamma amplifier. This gamma amplifier is a gamma corrector. Its

response has two gammas, 0.30 and 3.39. This response partially compensates the gamma nonlinearity at each end of the films exposure/density curve, thereby increasing the useful contrast range of the film. Following the gamma corrector is a black clipper that prevents the video from being stretched below the pedestal base line.

Circuit details of the gamma select system are shown in Figure 37.

3.4.7 Variable Bandwidth Filter

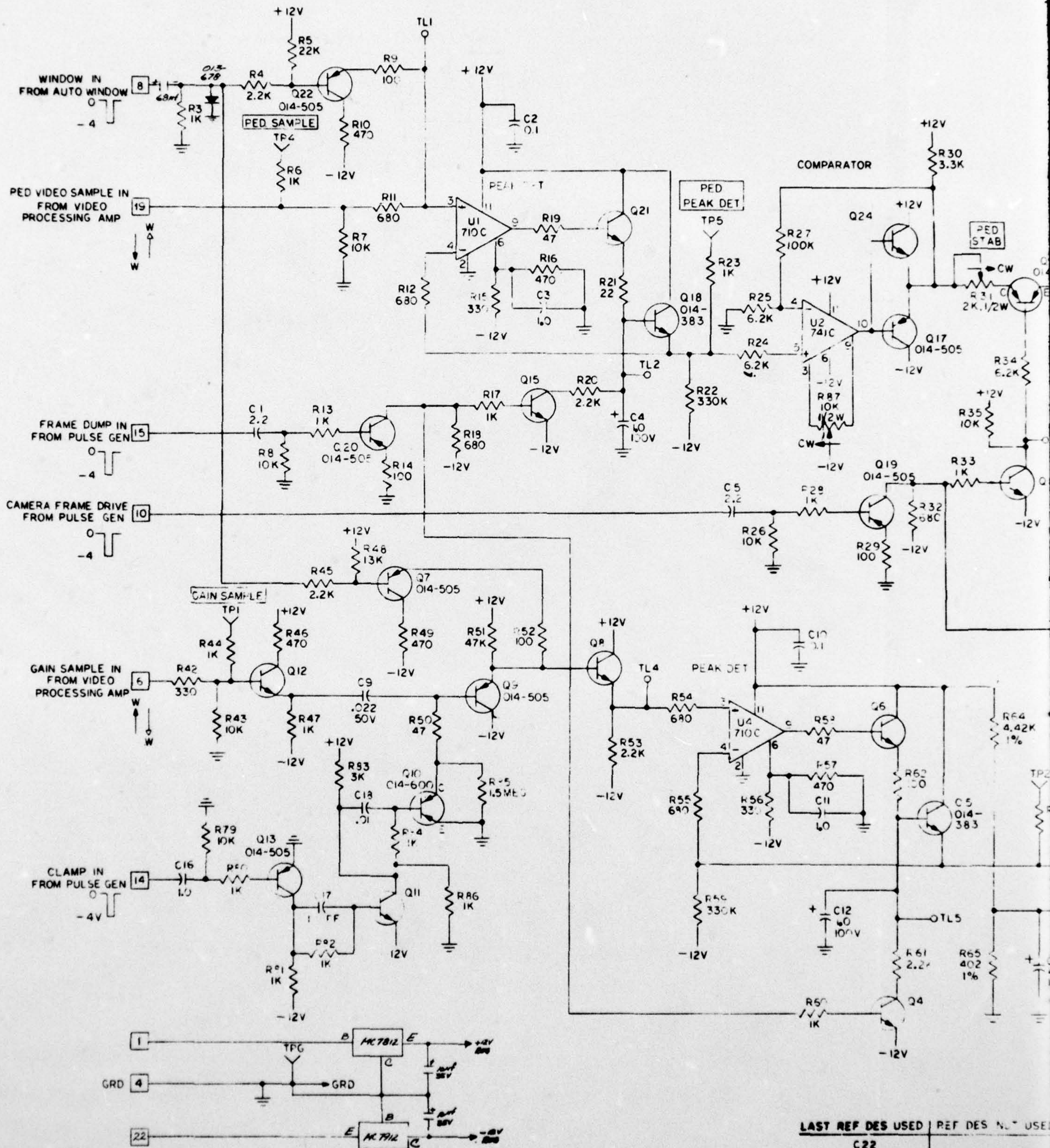
Referring to the block diagram of Figure 38, the variable bandwidth module permits the selection of four video signal bandwidths, 2,4,8 and 16 MHz. A front panel selector switch controls the logic of eight FET switches which select the input and output parts of any one of four low pass filters. The 2, 4, and 8 MHz low pass filters are phase compensated 3-pole Butterworth filters having a stop band attenuation of 18 dB/octave. The 16 MHz filter is a single pole filter having a monotonic roll-off of 6 dB/octave. A video amplifier and line driver makes up the termination loss of the filters. A second output is taken from the line driver and is fed back to the AGC control module. This closes the gain control loop and permits it to operate only on signals that are within the selected bandwidth. Circuit details are shown in Figure 39.

3.4.8 Modulator Pre-emphasis

Referring to the block diagram of Figure 40, the modulator preemphasis module produces the necessary high frequency compensation for the acousto-optical modulator and modulator driver. Transversal filters permit high frequency peaking while having negligible envelope delay distortion. Two such filters in tandem are required to obtain the necessary compensation. Circuit details are shown in Figure 41.

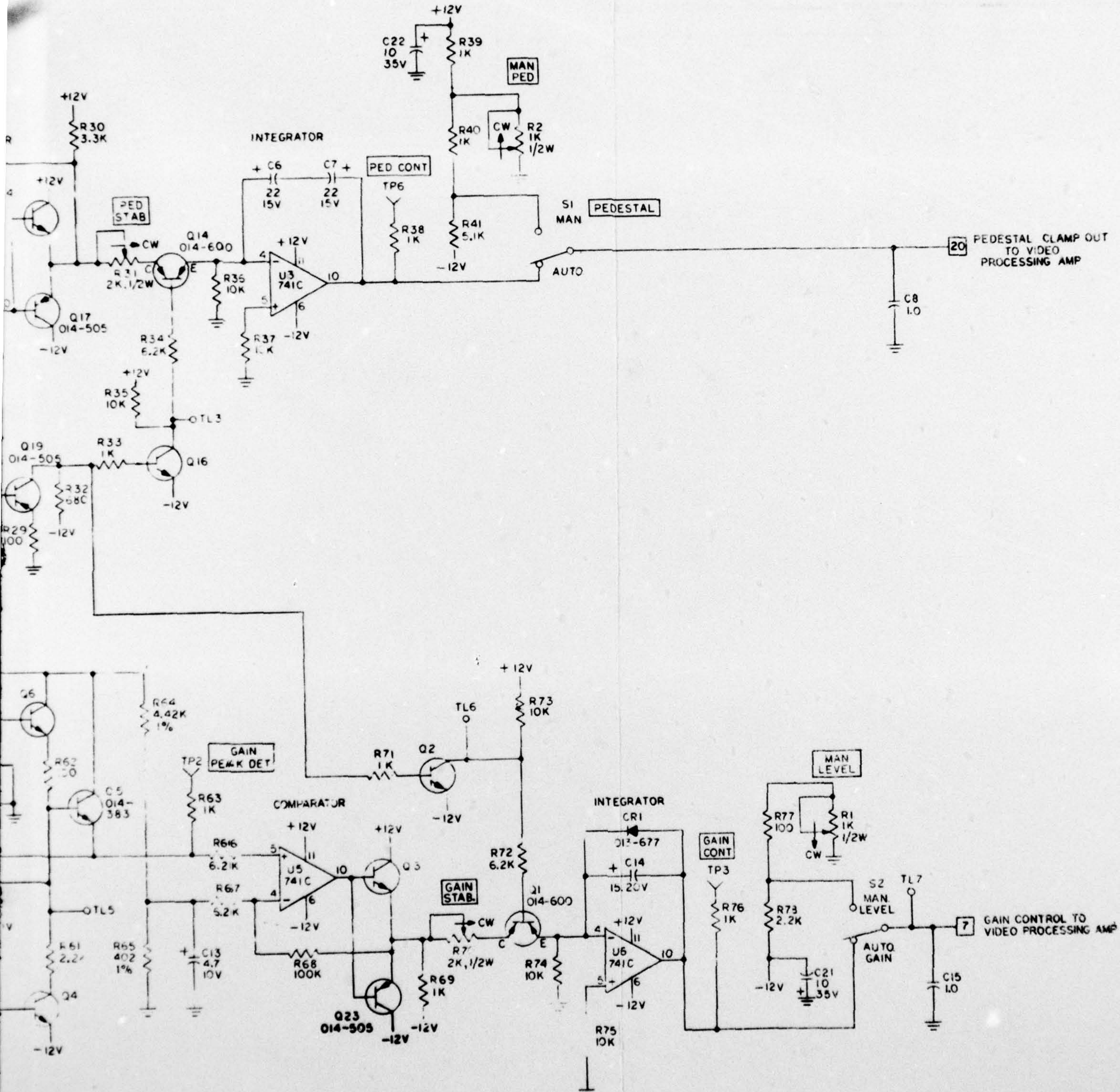
3.5 Acousto-optic Modulators

The r.f. to light transducers are commercial Datalite DLM-20 acousto-optic modulators. A modulator is required for each video channel.



NOTES:
1 UNLESS OTHERWISE SPECIFIED
- ALL RESISTOR VALUES ARE IN OHMS, 1/4W, 5%
- ALL CAPACITOR VALUES ARE IN MICROFARADS.
- ALL TRANSISTORS ARE PART NUMBER 014-248

LAST REF DES USED	REF DES NOT USED
C22	
Q24	
R97	
S2	
U6	
CR1	
TP6	
TPG	
TL7	



REF DES USED	REF DES NOT USED
C22 Q24 R57 S2 U6 CR1 TP6 TPG TL7	

Figure 35 AGC Control Block Diagram

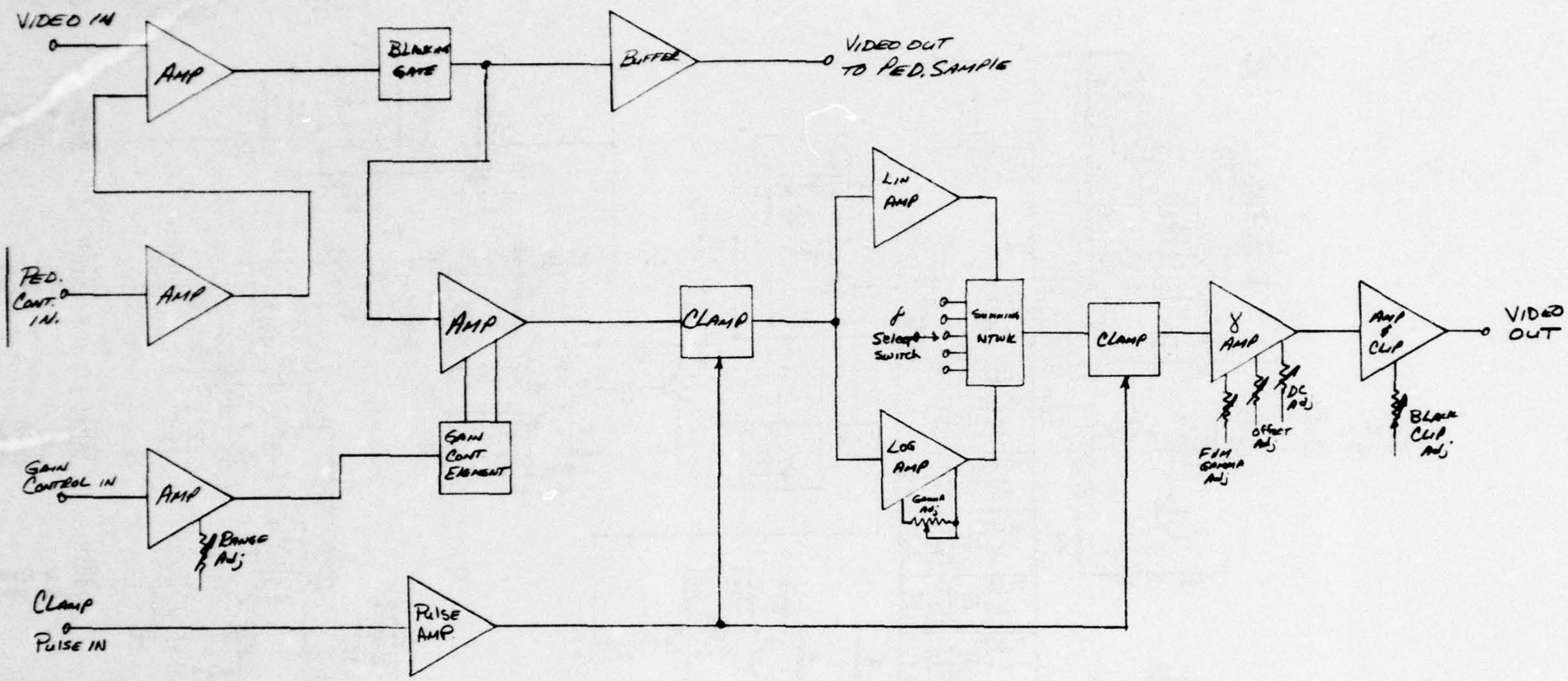


Figure 36 Gamma Control Block Diagram

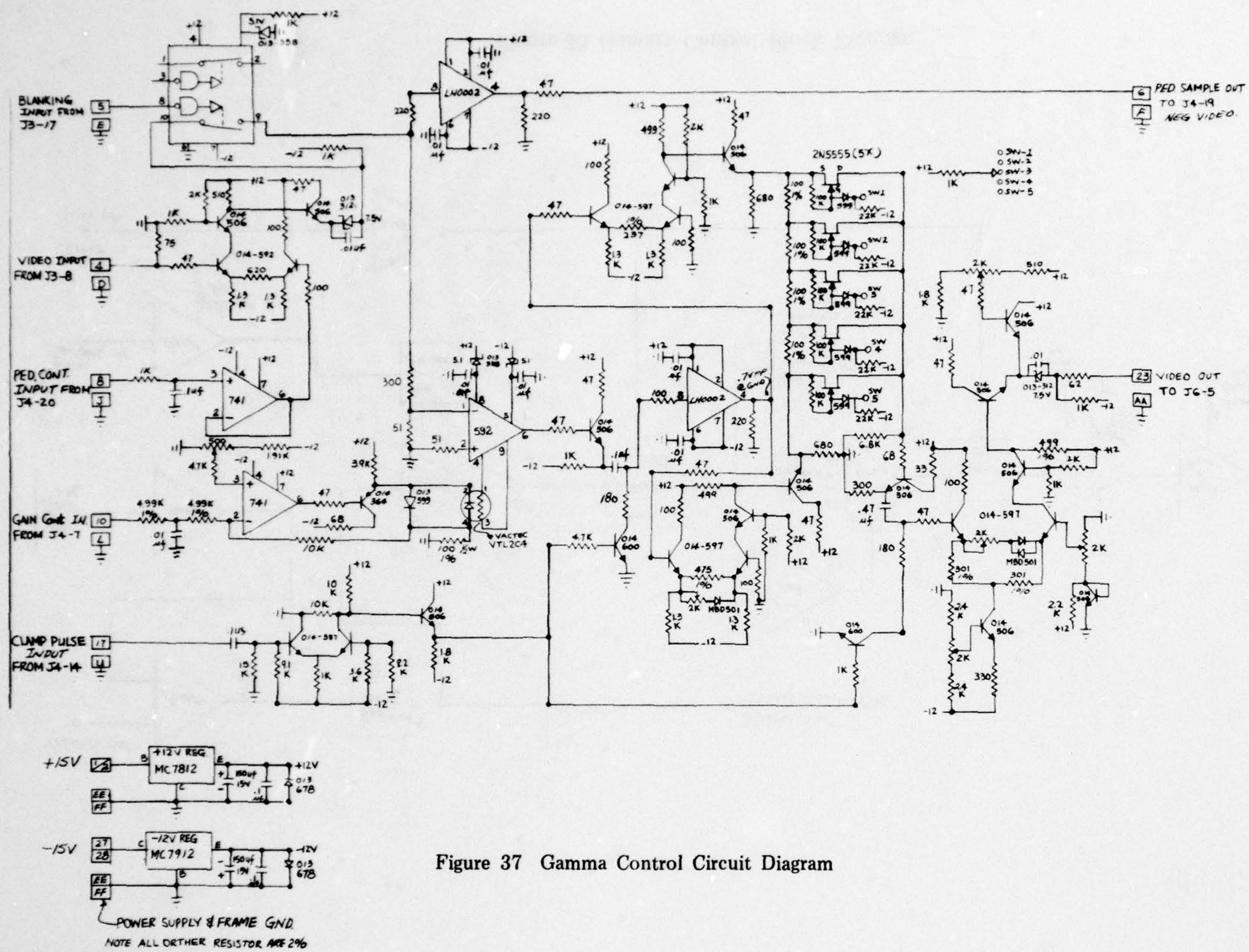


Figure 37 Gamma Control Circuit Diagram

AD-A050 615 AMPEX CORP REDWOOD CITY CALIF F/G 17/2
VIDEO LASER BEAM RECORDER.(U)
APR 77 L TEEPLE F33615-73-C-1152
UNCLASSIFIED RR-76-10 AFAL-TR-76-269 NL

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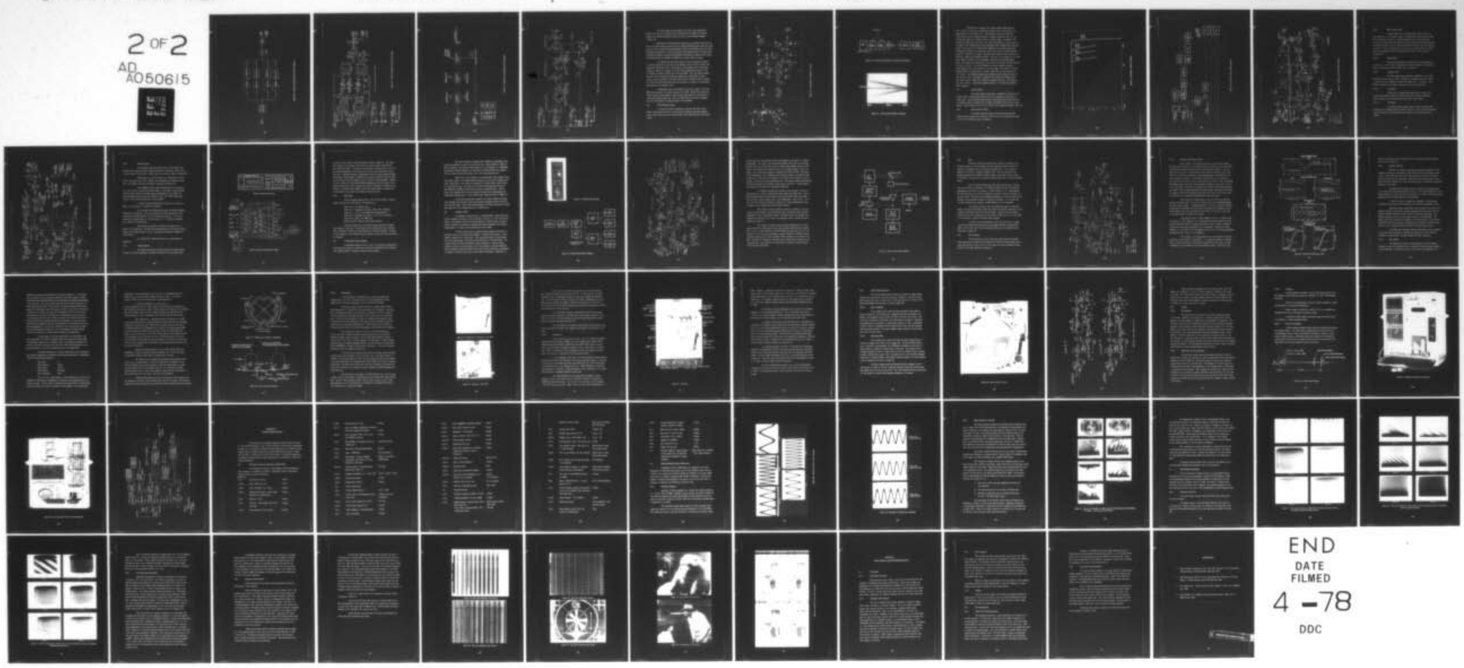
AD
A050615



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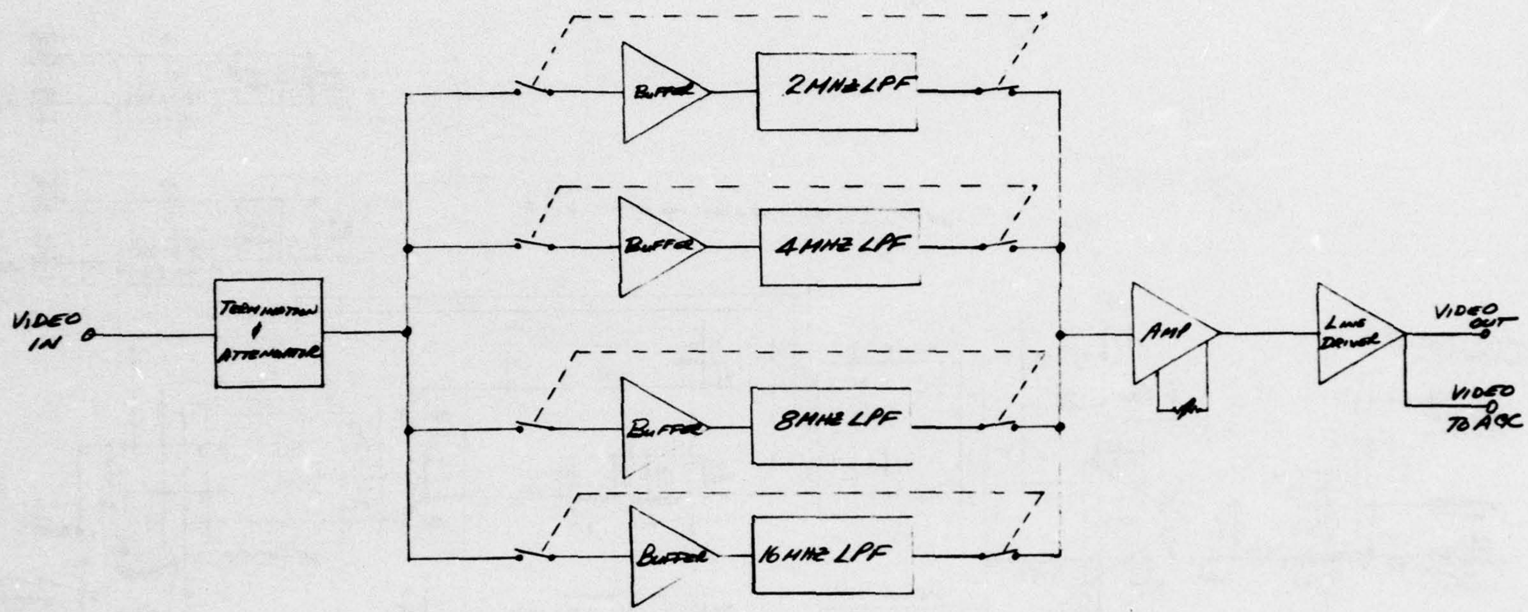
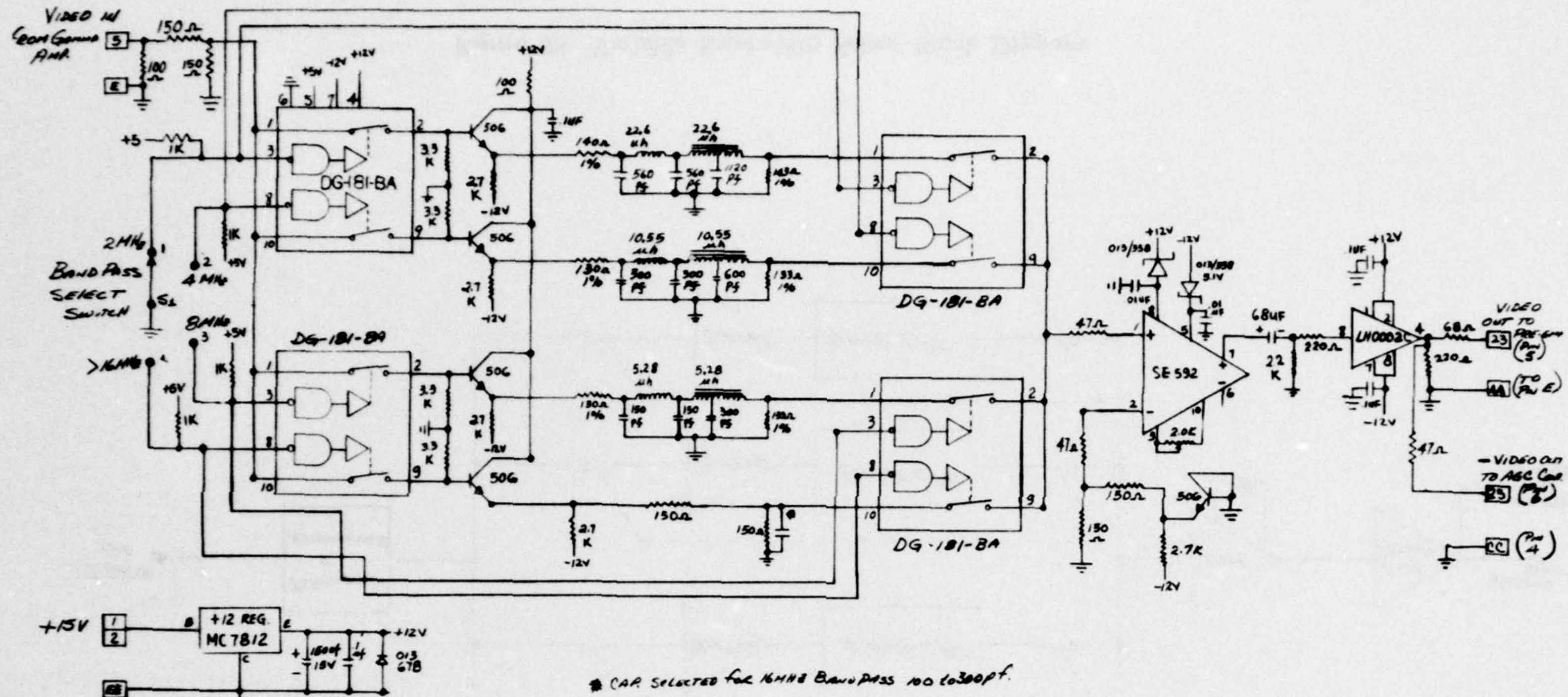


Figure 38 Variable Bandwidth Select Block Diagram



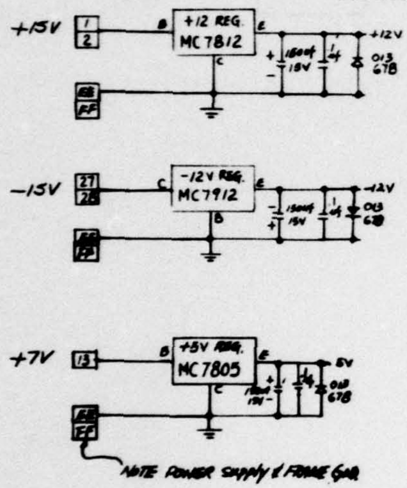


Figure 39 Variable Bandwidth Select Circuit Design

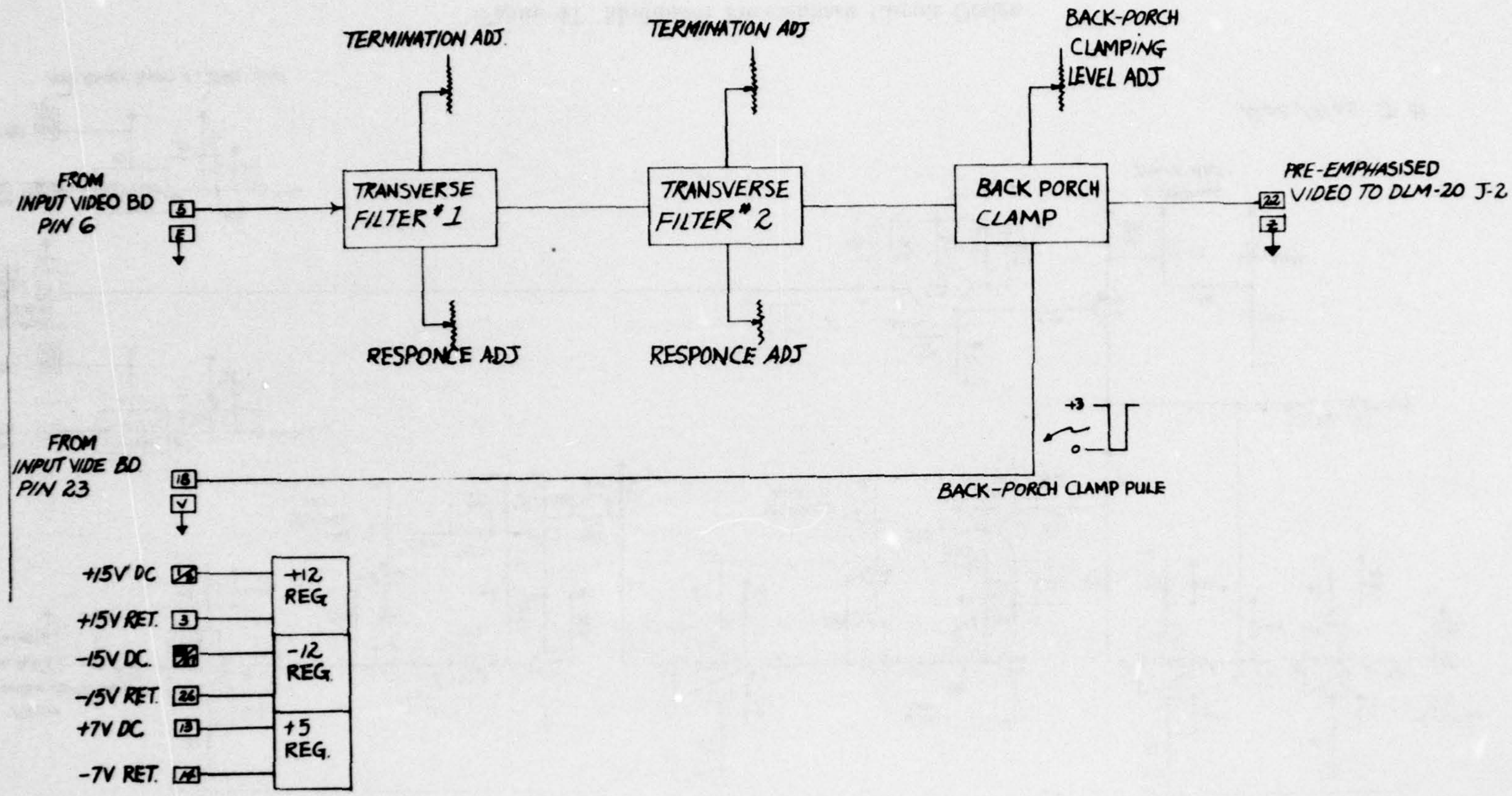


Figure 40 Modulator Pre-emphasis Block Diagram

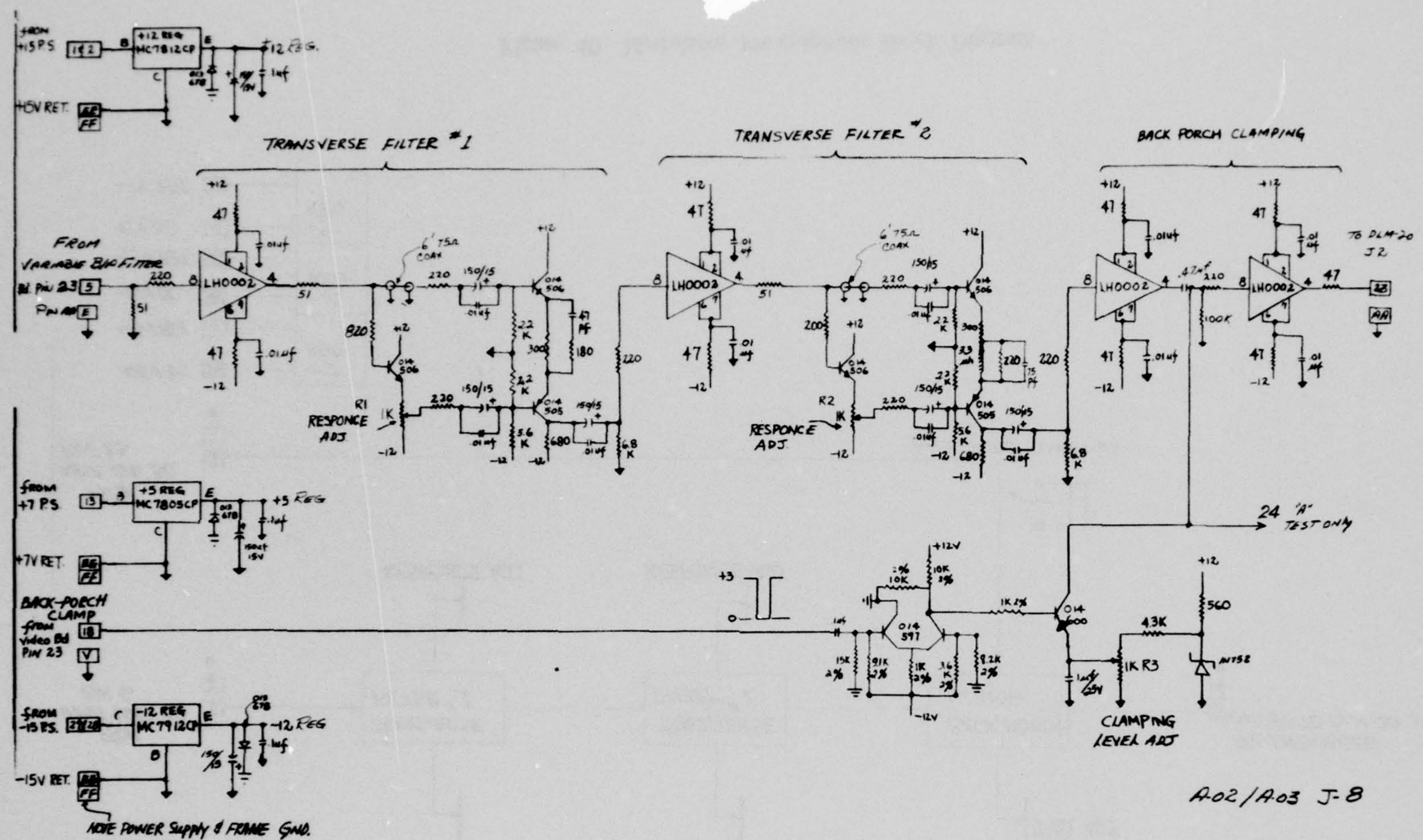


Figure 41 Modulator Pre-emphasis Circuit Design

The video signal, after processing in the video chain, described in Section 3.4, is fed to an oscillator-mixer manufactured by Datalight Corporation. Details of th oscillator-mixer-driver system are shown in the schematic diagram of Figure 42.

Referring to the block diagram of Figure 43, the oscillator-mixer unit consists of an 80 MHz oscillator which drives two tandem HP10534B mixers. The video signal from the Video Pre-emphasis Chassis amplitude modulates the 80 MHz carrier. The modulated signal is amplified in a solid state line driver. The amplified output of the mixer drives an Electronic Navigation Instruments Model 300P wideband power amplifier, which attains a 40 dB signal gain from .25 MHz to 110 MHz at an output power of 3 watts.

The risetime and frequency response of the acousto-optic modulator are chiefly determined by beam size in the transducer block, and the acoustic wave transit time through the beam. Performance of the modulator with a level signal is shown in Figure 44. Intensity in the first order (signal) beam output is -3 dB at 14 MHz, -4.3 dB at 16 MHz, and -6 dB at 20 MHz. The video signal emerging from the Video Pre-emphasis Chassis pre-emphasizes the video signal to yield a gamma corrected modulator output flat within 1 dB to 16 MHz as shown in Figure 45. The video signal input level causes the modulator to operate in a substantially linear portion of its response curve.

Considerable effort was expended to reduce the radiation of the 80 MHz carrier frequency into other systems of the VLBR. Cables were grouped and routed to reduce cross-coupling in other systems, particularly the various servos, to a level 40 dB below signal level. The coax cables between the power amplifiers also are braid shielded, the shield grounded at the amplifiers.

3.6 Film Transport Control

To achieve rapid film acceleration during start and stop cycles, a basket wound armature dc servo motor has been employed in the film transport system. This motor also has an integral basket wound tachometer for motor speed control.

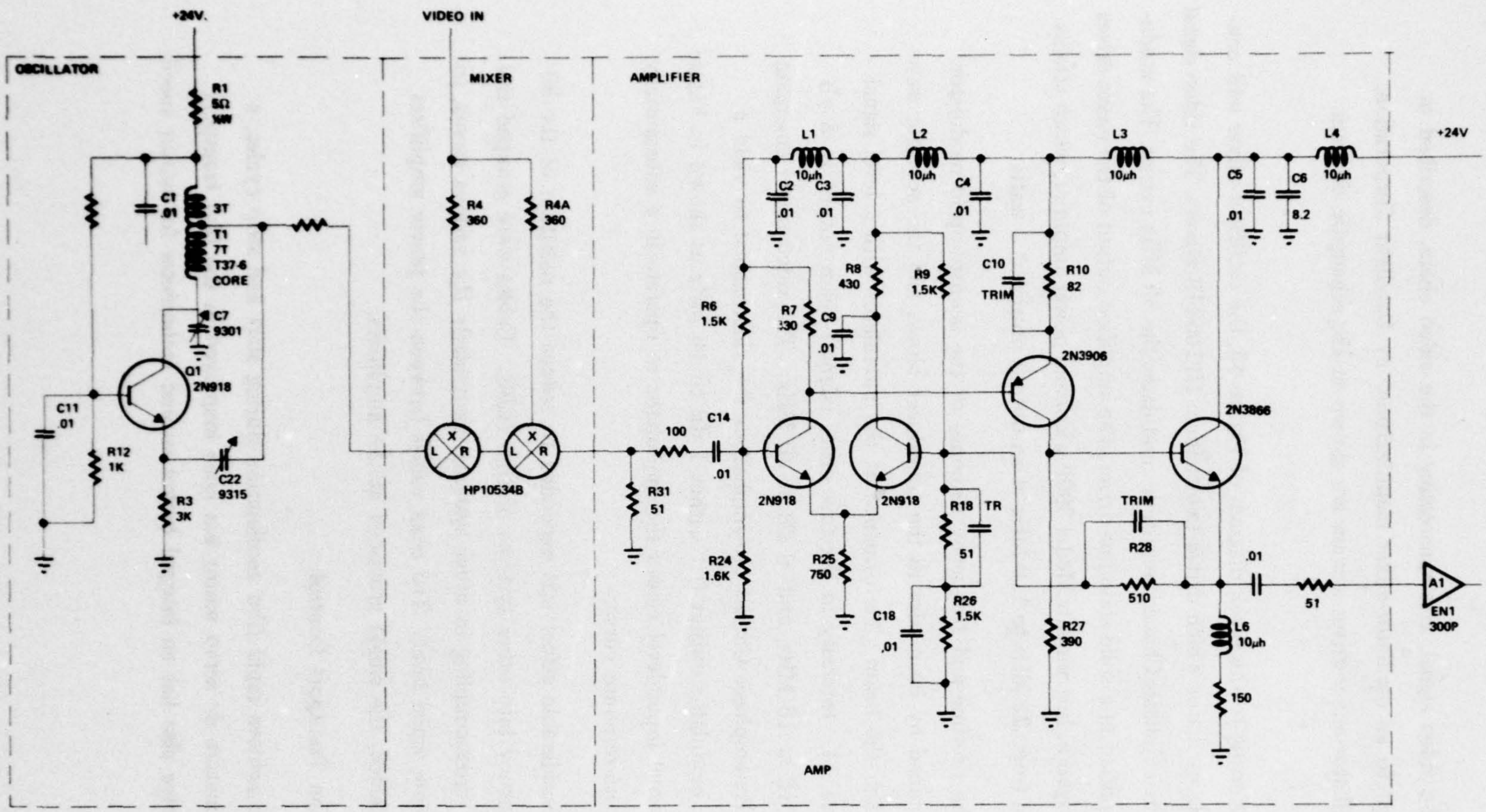


Figure 42 A/O Modulator Oscillator & Driver

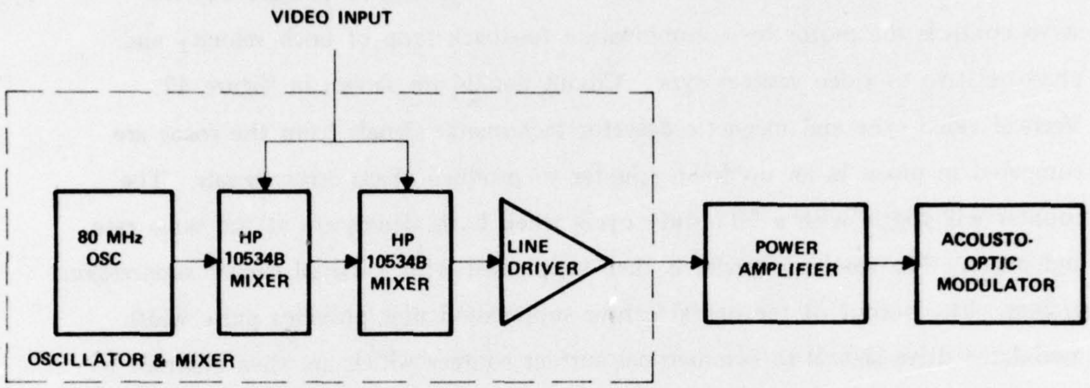


Figure 43 Acousto-optic Modulator System Block Diagram

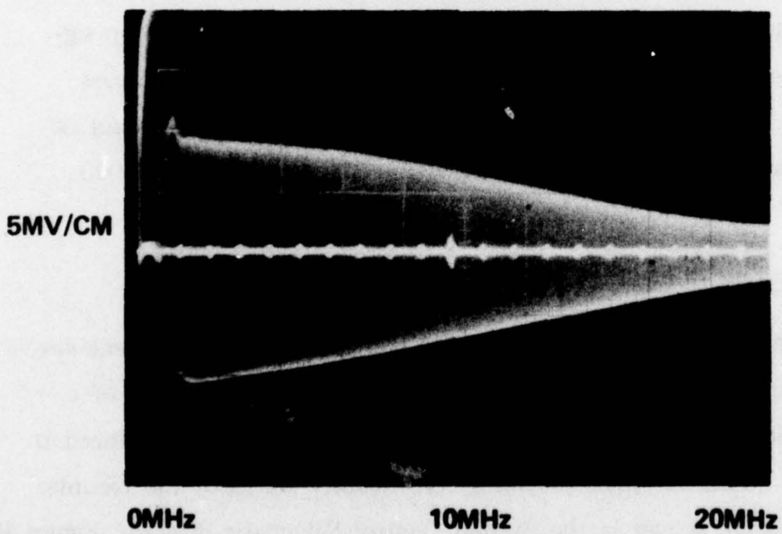


Figure 44 Acousto-optic Modulator Response

Referring to the transport servo block diagram (Figure 46) the servo controls the motor by a combination feedback loop of both velocity and phase relative to video vertical sync. Circuit details are shown in Figure 47. Vertical video sync and magnetic detector tachometer signals from the rotor are compared in phase in an up/down counter to produce phase error signals. The counter will toggle with a 50% duty cycle when both signals are at the same rate and phase. The resulting carrier is then suppressed with a digital carrier suppression system. The output of the digital carrier suppression unit provides pulse width modulated drive signals to symmetrical current sources which are then summed to provide the unfiltered error signal. The phase loop consists of three loop paths to provide an optimal gain bandwidth product. The first two loop paths are of conventional design in which the raw error signal is filtered by a 5-pole Butterworth filter. The output of the filter drives a dc loop and a lead loop with approximately 10 times the dc gain. To provide additional long term positional accuracy, a phase integrator loop is incorporated in the servo design. The output of the error summing mode is integrated over a 10 msec. period and at a gain 40 times the dc loop gain. The integrated signal is then summed with the other two loop signals and the velocity error signal. Inclusion of the velocity error signal ensures rotor phase lockup to video sync within the required one second. The output of this servo controls a motor drive amplifier employing a 100 watt RCA HC2000 power amplifier.

3.7 System Control

The record system control logic is organized to (a) prevent destructive failure modes and (b) locate the point of malfunction in the event of a system fault. Operating controls and function monitor lamps have been reduced to an absolute minimum consistent with providing recordability status of the recorder system. Circuit details are shown in the System Control Schematic diagram, Figure 48

3.7.1 Basic Interlock Chains

To prevent destructive failure of electronic and mechanical systems, system logic has been organized to shut down to the necessary level when any of the four interlock systems is triggered.

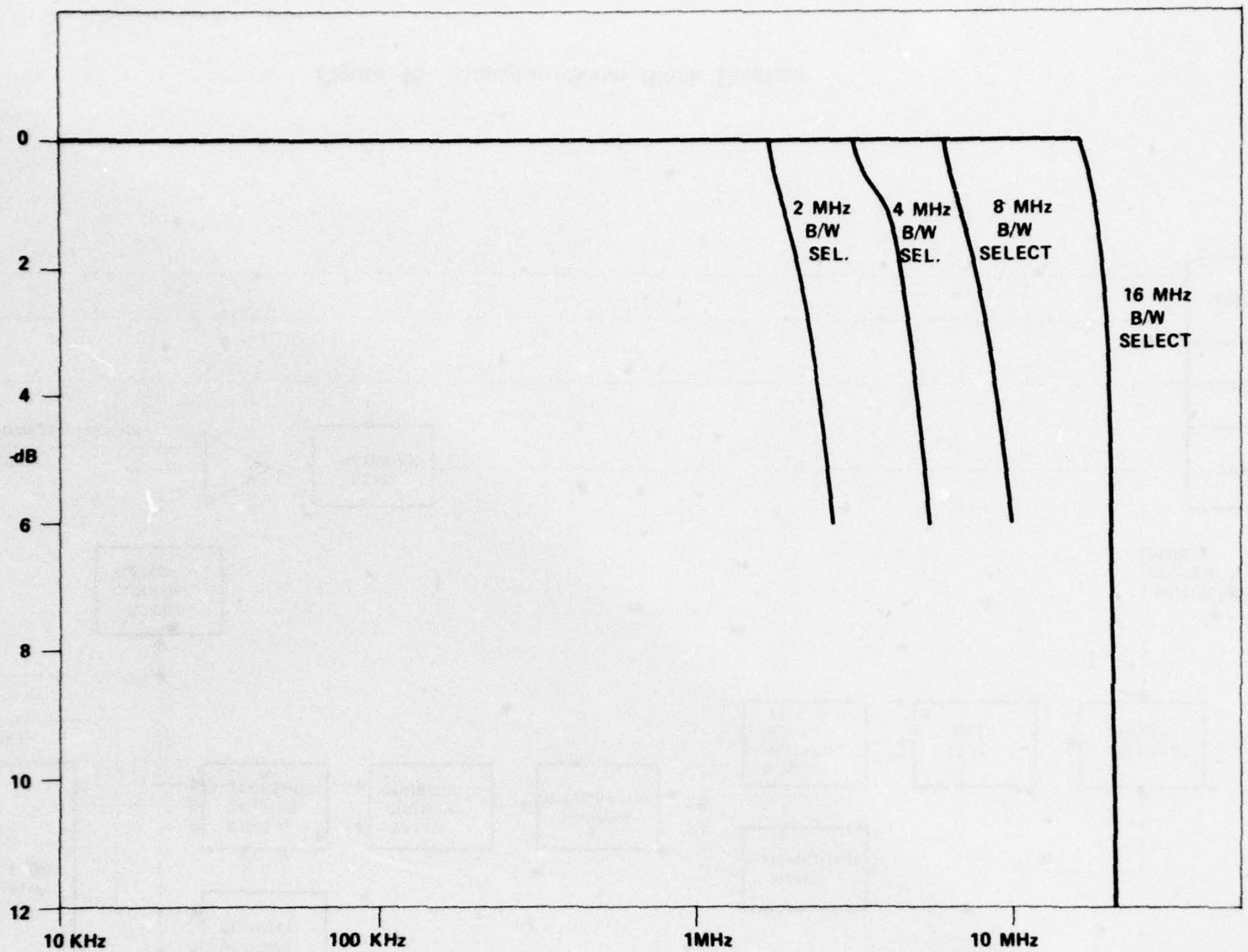


Figure 45 Modulator Optical Response

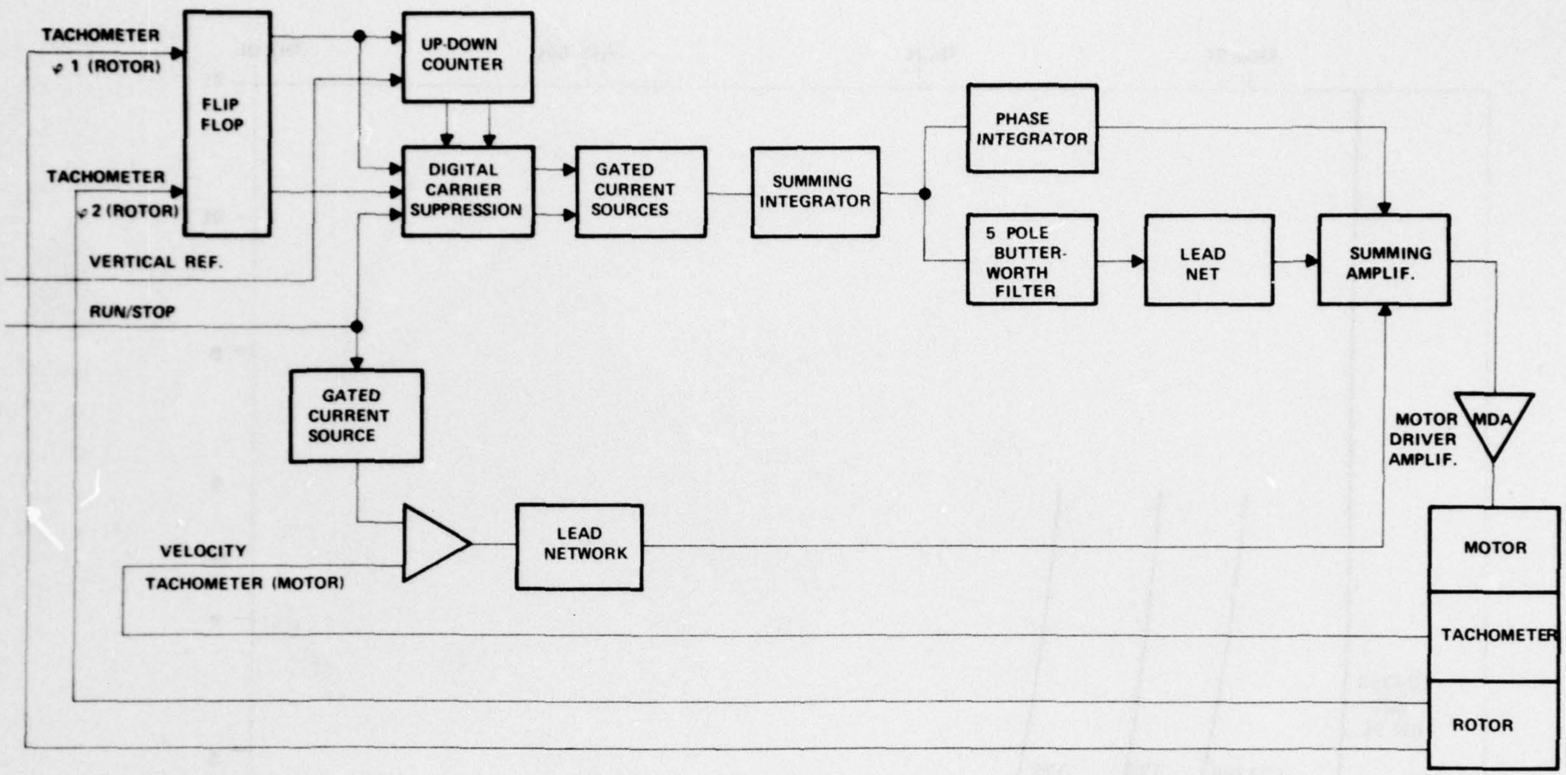


Figure 46 Transport Servo Block Diagram

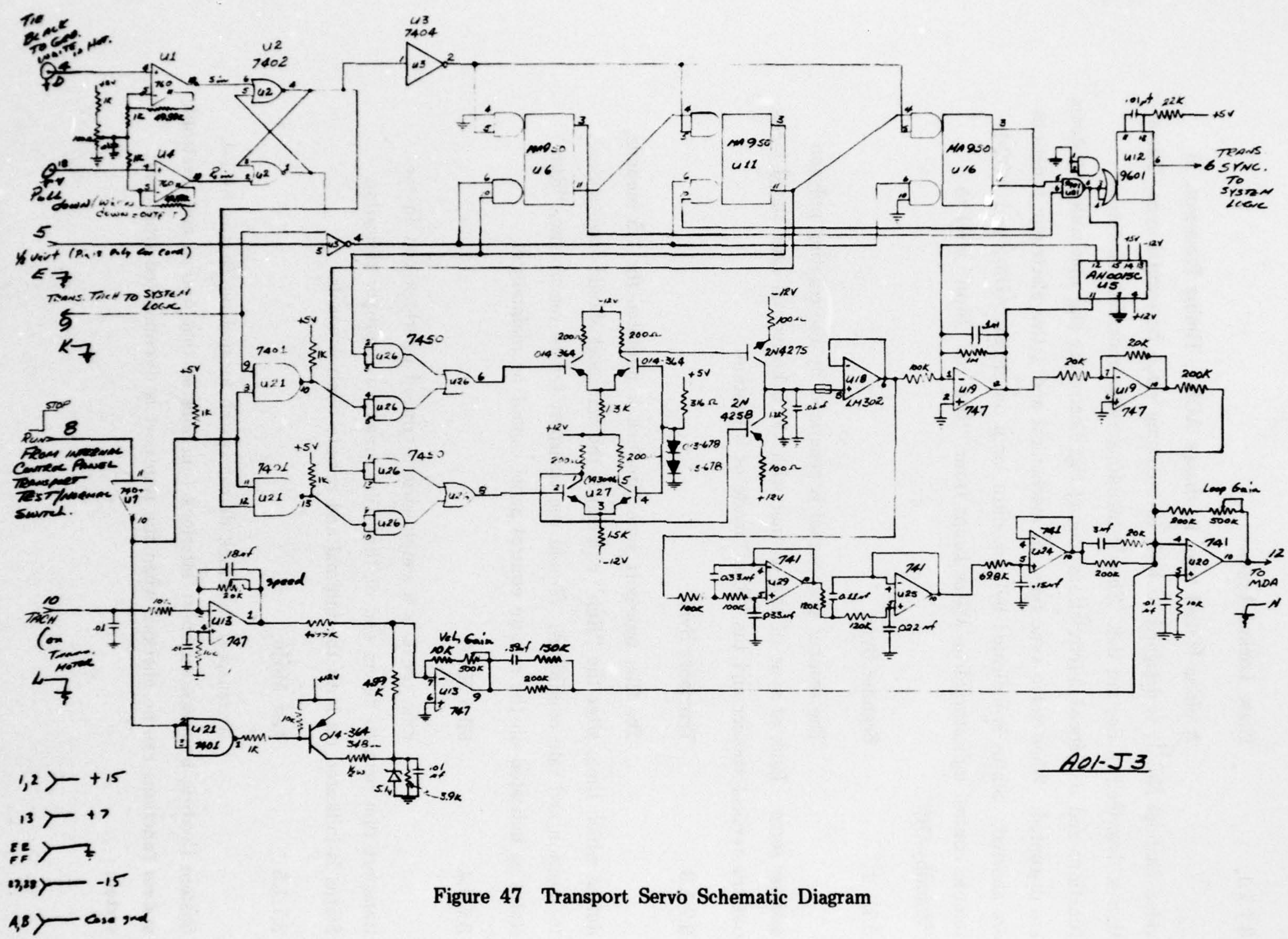


Figure 47 Transport Servo Schematic Diagram

3.7.1.1 Phase Locked Loop

A phase locked loop in chassis AO3-2, Timing Processor, in video channel No. 1, is designed to lock to incoming video horizontal sync. Operation is described in Section 3.4. Should incoming video sync fail, all timing functions and sequenced interrelations among the electronics and mechanical systems are disrupted. When video sync fails, all mechanical and active electronic functions are aborted. Status is indicated by a monitor lamp on chassis AO3-1 and AO2-1; remote control indicators drop status lamps from "Run" or "Stop" level to "Standby-Off".

3.7.1.2 Scanner Sync

The scanner sync signal is generated by the rotating polygon scanner servo. Lack of sync of the scanner with video horizontal sync signal locks out the vertical scanner and the "Run" mode of operation.

3.7.1.3 Transport Sync

The film transport sync interlock is inhibited for 1.5 seconds, during which time, after the "Run" command, the transport should have locked to position and rate conditions. Should the transport fail to reach sync, "Run" status as indicated on the remote control panel cannot be maintained.

3.7.1.4 Film Break

Film break is a simple switch tripped interlock pair in the transport film path to detect end of film, film break, or improper threading. Status is indicated on both the internal and remote control panels.

3.7.1.5 Test Mode

A transport interlock defeat switch located on chassis AO1-4, System Control, bypasses transport interlock functions so that optical and electronic system functions can be checked when the transport is disconnected from the system.

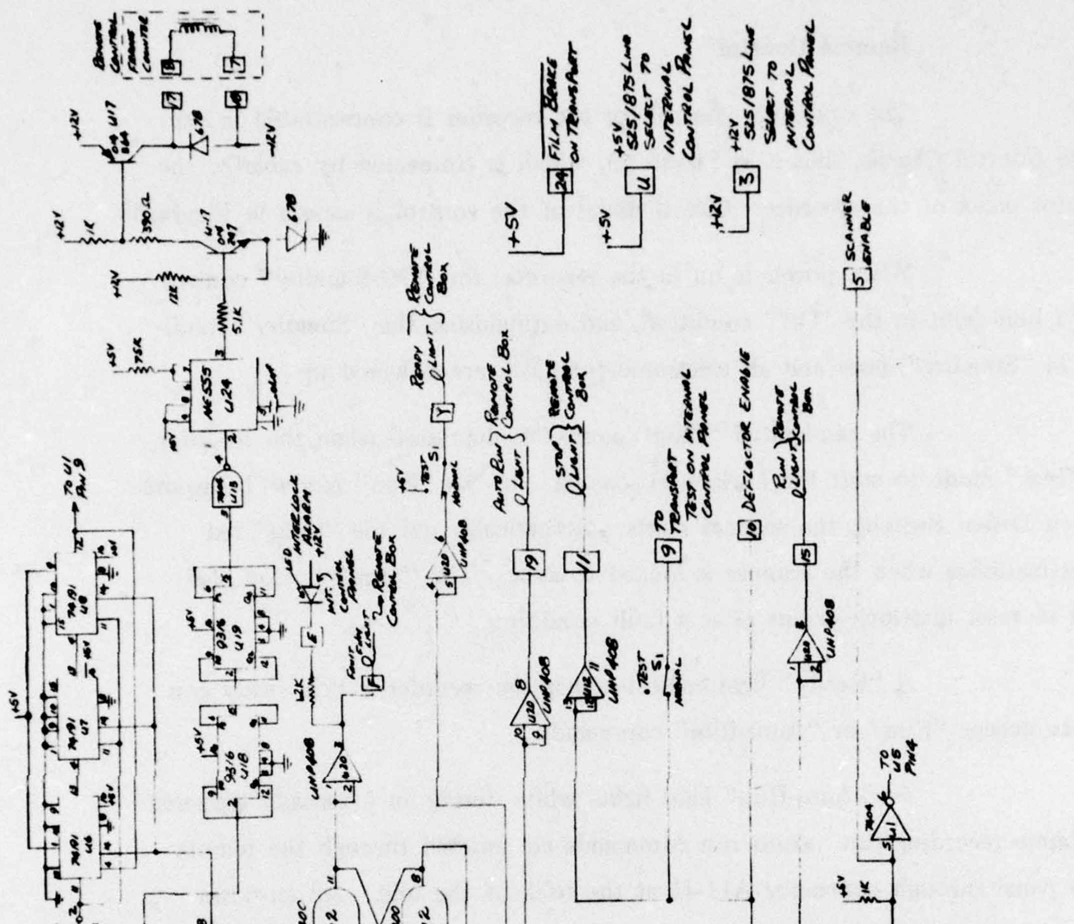


Figure 48 System Control Schematic Design

3.7.2 Remote Control

The operating control for the recorder is concentrated in the Remote Control Chassis, shown in Figure 49, which is connected by cable to the connector panel of the recorder. Circuit detail of the control is shown in Figure 50.

When power is on in the recorder, the "Off-Standby" control shows a blue light in the "Off" condition, and extinguishes the "Standby" condition. In "Standby", laser and all electronic functions are powered up.

The red-lighted "Stop" control is depressed when the recorder is in "Test" mode to start the horizontal scanner. In the "Run" mode (Transport Interlock Defeat Switch), the scanner starts automatically and the "Stop" red light extinguishes when the scanner is locked to sync. The "Stop" button also is used to reset interlock chains after a fault condition.

A "Ready" light indicates that the recorder is in a ready condition to accept "Run" or "Auto-Run" commands.

An "Auto-Run" light lights white during an externally triggered 1802 frame recording run. Auto run commands are entered through the remote control panel through connector A11-J1 at the back of the unit. An auto-run command is a signal 20 μsec to 1 ms in duration of 3 to 32 volts in amplitude into a 3000 ohm balanced input.

The recorder is actuated at the panel by pushing the blue lighted "Run" pushbutton. The light will extinguish during the recording operation as long as all interlock chains are clear. The recorder is stopped by pressing the "Stop" button.

The "Film Fault" indicator also serves as a panel lamp test pushbutton.

3.7.3 Internal Control

An internal control panel mounted within the recorder cabinet provides control and monitoring for functions associated with prerecording setup

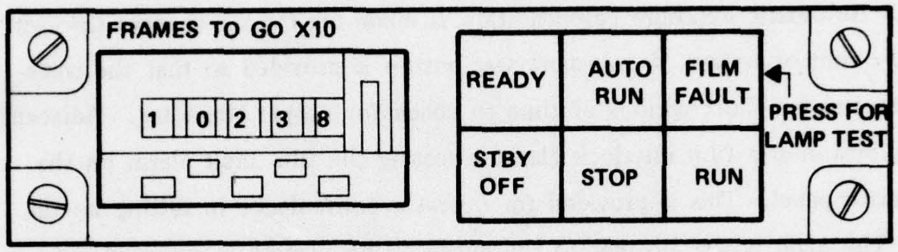


Figure 49 Remote Control Panel

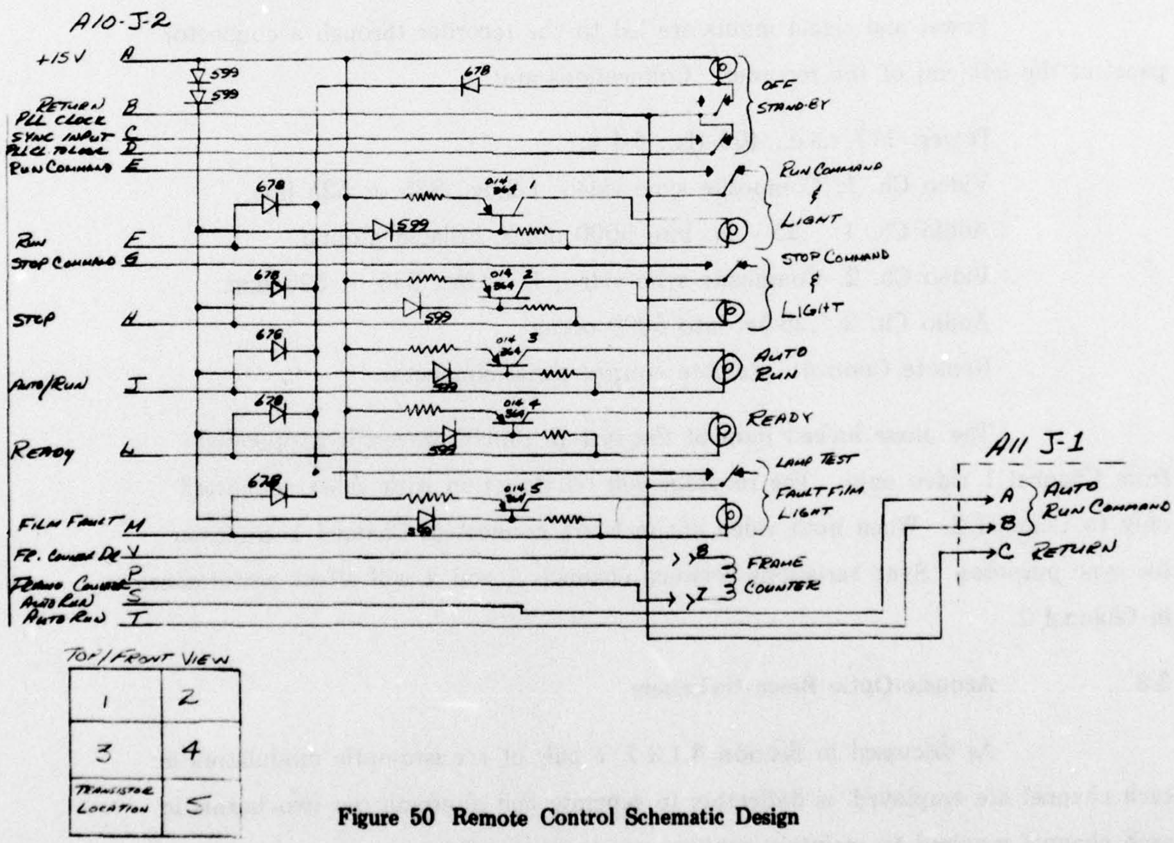


Figure 50 Remote Control Schematic Design

and check of the recorder. The panel detail is shown in Figure 51. The upper most control on the internal control panel is line rate selection offering either 525 or 875 line format. An exposure control which is calibrated from zero to 10 and provides adjustment of the beam power level for proper exposure of various film types. Automatic exposure compensation is made for format changes through the intensity control system. A transport test button is provided so that the transport may be run for short periods of time to check for proper threading. Adjacent to this test button is a film interlock alarm repeating the film fault alarm on the manual control panel. This is provided for operator convenience in setting up the transport. The main power breaker to the entire VLBR system is mounted also on the internal control panel and provides the primary power.

3.7.4 Input Panel

Power and signal inputs are led to the recorder through a connector panel at the left end of the recorder. Connections are:

Power: 117 v.a.c., 400 Hz., 6.4 a.

Video Ch. 1: Composite sync video, 1-2.5v., 875 or 525 line.

Audio Ch. 1: .25 - 5v. into 5000 ohms, isolated ground.

Video Ch. 2: Composite sync video, 1 - 2.5v., 875 or 525 line.

Audio Ch. 2: .25-5v. into 5000 ohms.

Remote Control: Remote control panel connector.

The phase locked loop of the system timing processor is operated from Channel 1 video only. The recorder will not function with video connected only to Channel 2. When both video channels are connected, Channel 1 is master for sync purposes. Sync variations between channels 1 and 2 will affect performance in Channel 2.

3.8 Acousto-Optic Beam Switchers

As discussed in Section 3.1.3.7, a pair of acousto-optic modulators in each channel are employed as deflectors to separate and alternate the two beams in each channel required to maintain continuous access scanning.

The beam switchers are Datalight Model DLM-1 a/o modulators which have been modified to pass a 6 mm clear laser beam. Beam deflection at 633 nm beam wavelength at the 45 MHz carrier frequency of the modulator is 7 milliradians. As previously indicated, deflectors are alternately fed gated 45 MHz drive signals to direct the beam down alternate paths in sync with video horizontal sync.

Figure 52 is a block diagram of the acousto-optic beam switcher system. The system consists of a 45 MHz generator followed by a line driver amplifier which feeds a diode switch. The switch is controlled by the switch driver which is driven at ½ the horizontal rate. The output of the diode switch alternately drives two ENI 300P power amplifiers which provide 3 watts of gated RF power. Each of these power amplifiers drive two acousto-optic deflectors, thus commutating both optical paths simultaneously. Circuit details of the system are shown in Figure 53.

As with the acousto-optic modulators, the cross coupling of the high power 45 MHz drive systems to video and mechanical equipment servos and control was a serious problem. Only after double-shielding and carefully grouping and routing drive cables was cross coupling reduced to a tolerable level.

3.9 Intensity Control

As discussed in Section 3.1.3.2, a Datalight DLM-1 acousto-optic modulator is installed at the head of the optical path to function as a laser beam power control. The intensity control has been incorporated in the laser beam recorder as shown in Figure 54 to provide the required laser output stabilization and exposure compensation for a range of film sensitivities and scan formats.

Control of beam power is achieved through amplitude modulation of the drive carrier of an acousto-optic modulator. Following the modulator, a beam splitter is inserted in the output beam. The beam splitter picks off approximately 4% of the radiant energy. This beam is then detected by a PIN photodiode. The current produced by this photodetector is then compared to a preset reference current as set by the current reference unit. The reference is manually adjustable from the exposure control mounted on the internal control panel and is programmed to respond to changes in line format of 525 and 875 lines/frame. Differences in

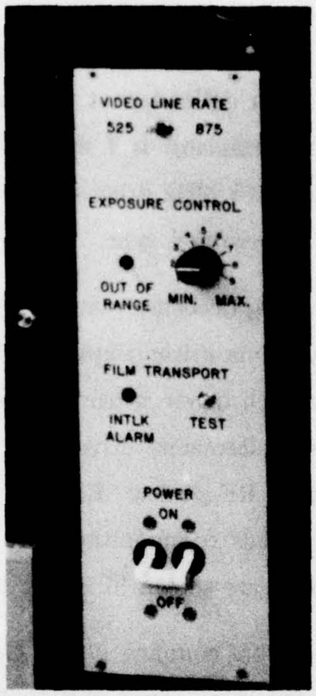


Figure 51 Internal Control Panel

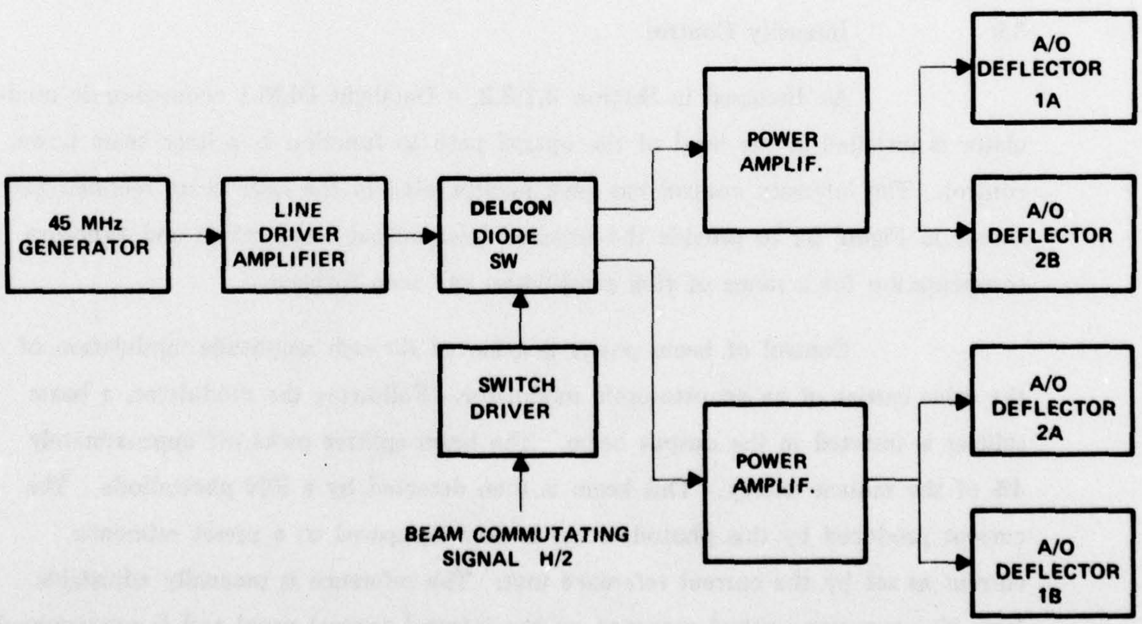


Figure 52 Beam Switcher Block Diagram

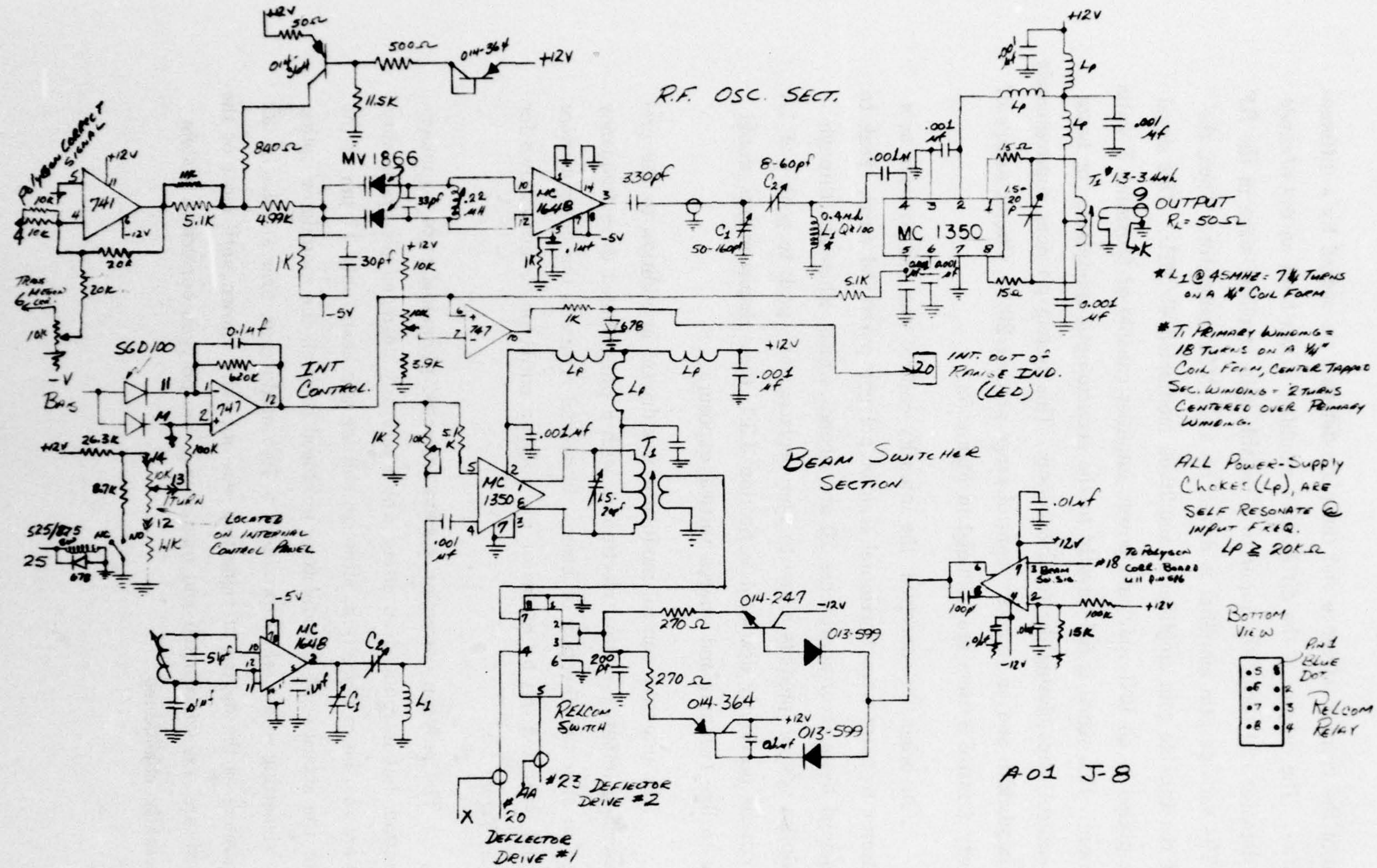


Figure 53 Beam Switcher Control & Oscillator

current from the current reference and the photodetector are sensed by a differential amplifier. The output of the differential amplifier drives both an out-of-range indicator detector and forms the input to a variable gain amplifier stage in the RF section. The variable gain amplifier is driven by a 45 MHz generator. Thus, the output of the variable gain amplifier is amplitude modulated 45 MHz. This signal is then amplified in an ENI wideband power amplifier capable of providing 3 watts of RF power. This signal is fed directly to the acousto-optic modulator for beam intensity control, thus closing the feedback loop. This system provides approximately 100 kHz bandwidth and an intensity control range of over 20:1. Circuit details of the Intensity Control System are included in Figure 53.

As originally conceived, the intensity control was also to serve as a beam deflector to correct for horizontal scanner polygon pyramidal error. Peak to peak pyramidal beam error approaches 20 arc seconds which, when put through the scan optics system, predicts a line to line displacement - peak to peak - of 1.7 μm. By criteria previously discussed in Section 3.3.1, these displacements would contribute to line twinning and uneven vertical exposure.

The intensity control modulator was driven, in addition to the previously described intensity control electronics, with a programmed drive frequency modulation to alter the direction of beam. Pyramidal errors of the polygon were observed and corrected out by means of the polygon corrector circuits, shown for reference in Figure 55.

The polygon correction system corrected pyramidal error to under one arc second, but introduced an effect which seriously degraded picture quality. The $\pm$ 10 arc sec. beam deflection, although shifting the beam only 17 μm at the entrance to the acousto-optic modulators, produced through the modulator optics, a periodic vignetting effect which produced a 35% modulation over a series of 32 lines. Inasmuch as the degree of vignetting was not fully known until most of the system hardware was constructed and operational, the polygon correction system was reluctantly abandoned.

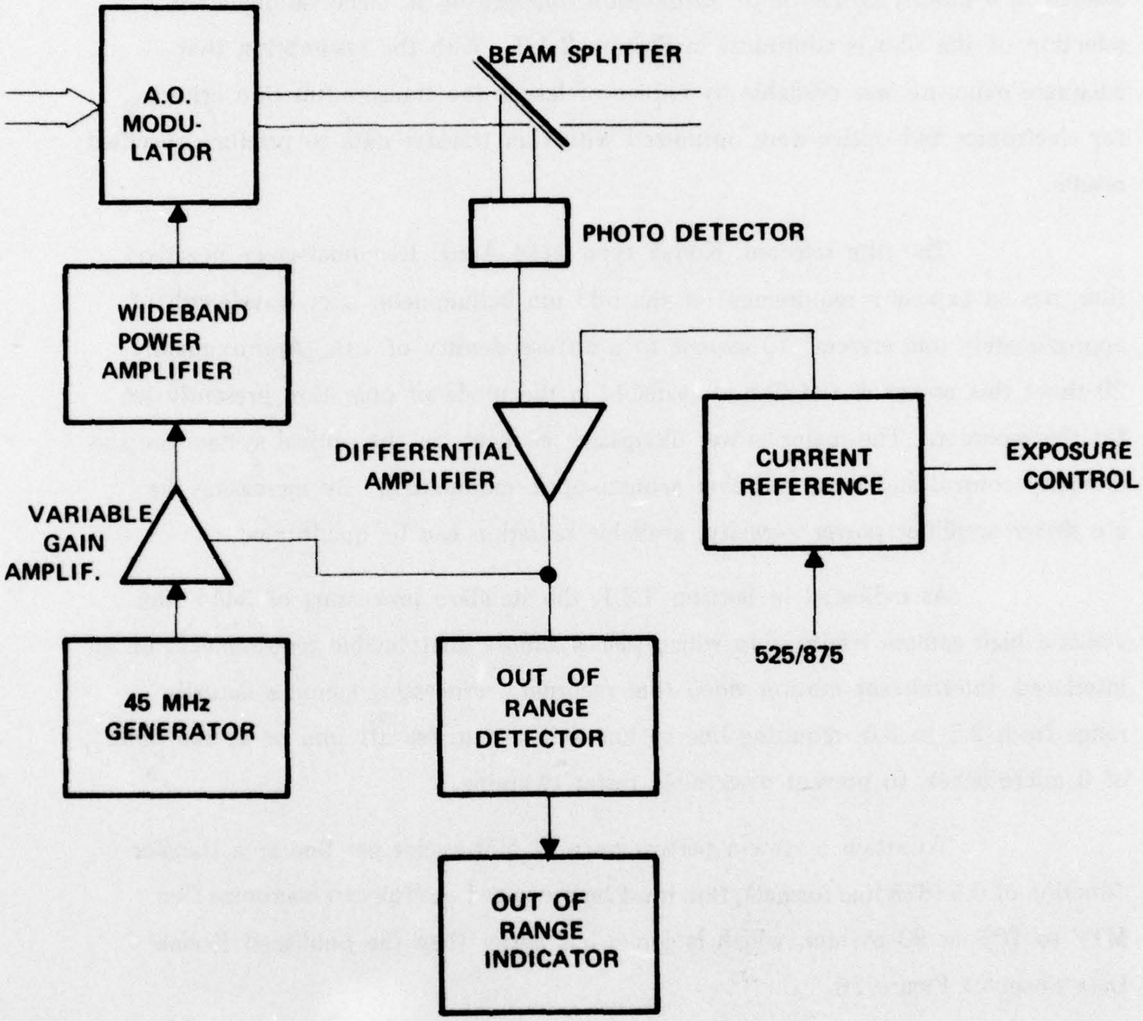


Figure 54 Intensity Control Block Diagram

3.10 Film

The film, as discussed in Section 2.4.1, must be considered in any recording system, as a system element, and the modulation transfer function considered as a modifying factor to information imposed on it. The rationale for selection of the film is continued in Section 2.4.2. With the assumption that adequate exposure was available by choice of lasers, the transfer function criteria for electronics and optics were optimized with film transfer data to produce specified results.

The film selected, Kodak type 3414 Aerial Reconnaissance negative film, has an exposure requirement at the 633 nm helium-neon laser wavelength of approximately one erg/cm^2 to expose to a diffuse density of 1.0. Approximately 20 times this power at the film is available in the mode of operation presently set for the recorder. The major power dissipating elements in the optical system are the intensity control and beam switcher acousto-optic modulators. By increasing the a/o driver amplifier power capacity, available radiation can be quadrupled.

As indicated in Section 3.3.1, the standard processing of 3414 film yields a high gamma relationship which places almost unattainable requirements on an interlaced, intermittent motion video film recorder. Processing gammas actually range from 2.5 to 3.6, requiring line to line shifts of under .01 μm, or of the order of 3 microinches, to prevent discernible raster twinning.

To attain a system performance of 500 cycles per line at a transfer function of 0.5 (875 line format), film must be processed carefully to maximize film MTF to 70% at 90 cy/mm, which is somewhat better than the published Kodak Data Sheet of Figure 56.

3.11 Film Transport

The film transport for the Video Laser Beam Recorder essentially must transport and constrain the film during the recording of high resolution interlaced video pictures in such a way as to not affect the system modulation transfer function of the video-optics-film combination.

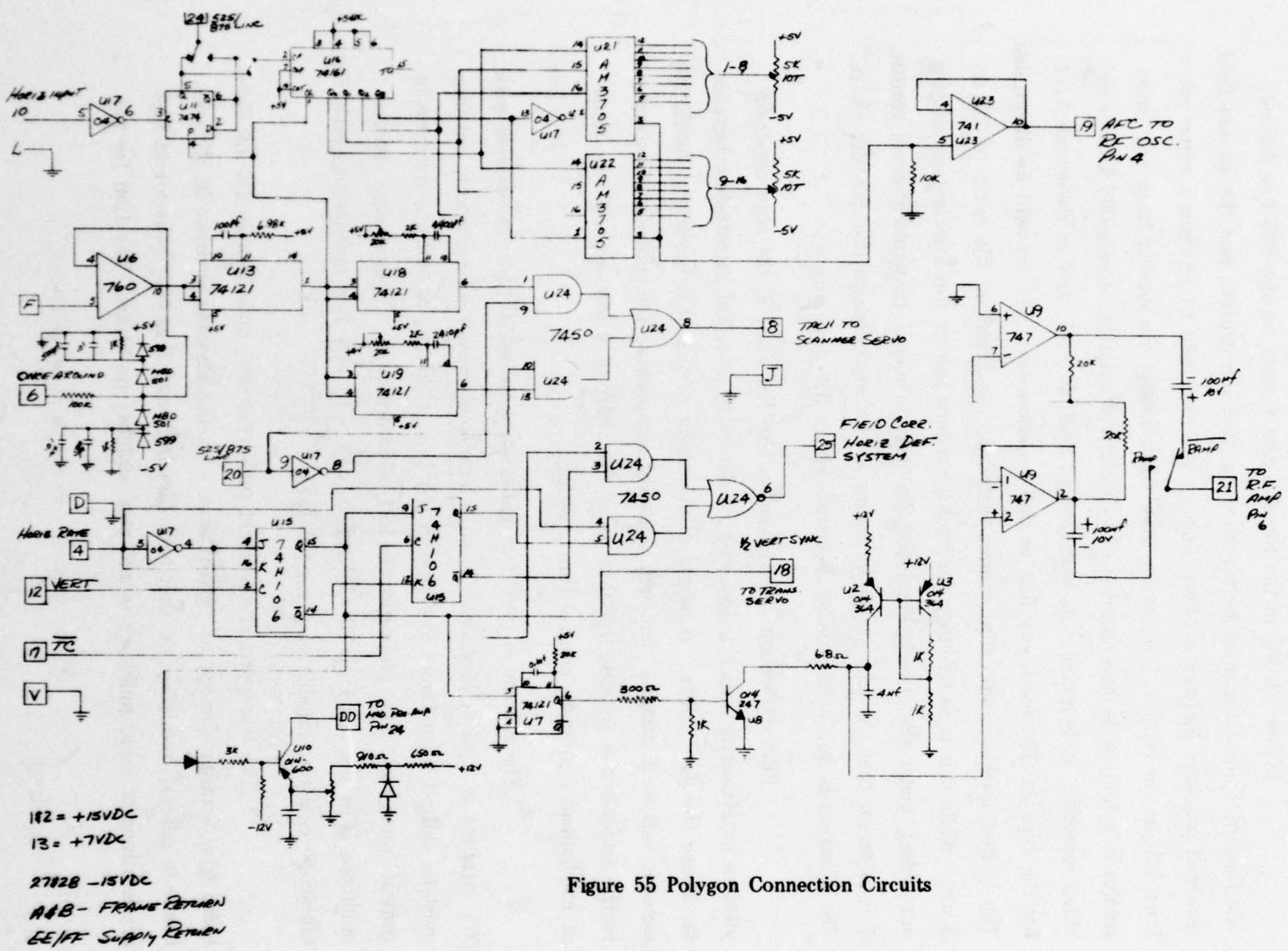


Figure 55 Polygon Connection Circuits

3.11.1 Transport Performance Criteria

In the VLBR, in the Super-8 mm format, at the 875 line format, one field of 6 μm lines must be recorded on 10.6 μm centers, and the second field recorded precisely halfway between lines of the first field to produce a raster of lines 5.3 μm on centers. Departure from equal raster line spacing from any cause results in a noticeable non-linearity of pictorial presentation, commonly known in video recording as twinning. As discussed in Section 3.3.1, and in Reference 1, for the type of film used, any line to line variation over .011 μm will be discernible. The highest quality studio film camera maintains steadiness on the order of 2.5 to 5 μm. While this is satisfactory for analog systems (direct through-the-lens imaging onto film), under the criteria developed for raster cameras, particularly small format, it is apparent that the film transport looms as the weak link in the recorder chain. The situation is not substantially alleviated with a 525 line format.

Film movement or displacement of line start in the scan direction yields a non-linearity which is less easy to detect by eye, but nonetheless degrades the image transfer quality. A lateral displacement of 0.2 of a horizontal resolution element will be discernible, and will seriously compromise the information transfer. In the Super-8 mm format, this limit is of the order of 2 μm, again at the limit of mechanical devices to control film position.

The maximum period of video blanking at 30 f.p.s. in pictures with 2:1 interlace is 1.33 millisecond. In an intermittent movement transport, the film must be shifted from frame to frame in less than 1.33 ms, or suffer a decrease in vertical frame size, with proportionate loss of information. Typical cine camera pulldown is of the order of 10 - 20 millisecond with very few mechanisms, including kinescope cameras, capable of 4 ms pulldown.

The transport, at the rapid pulldown rate, must handle 2½ mil Estar based film without damage to perforations. A considerable decrease in stiffness, hence in natural frequency, of thin base film indicated that film behavior at high accelerations of rapid pulldown would pose stability problems. The film for the

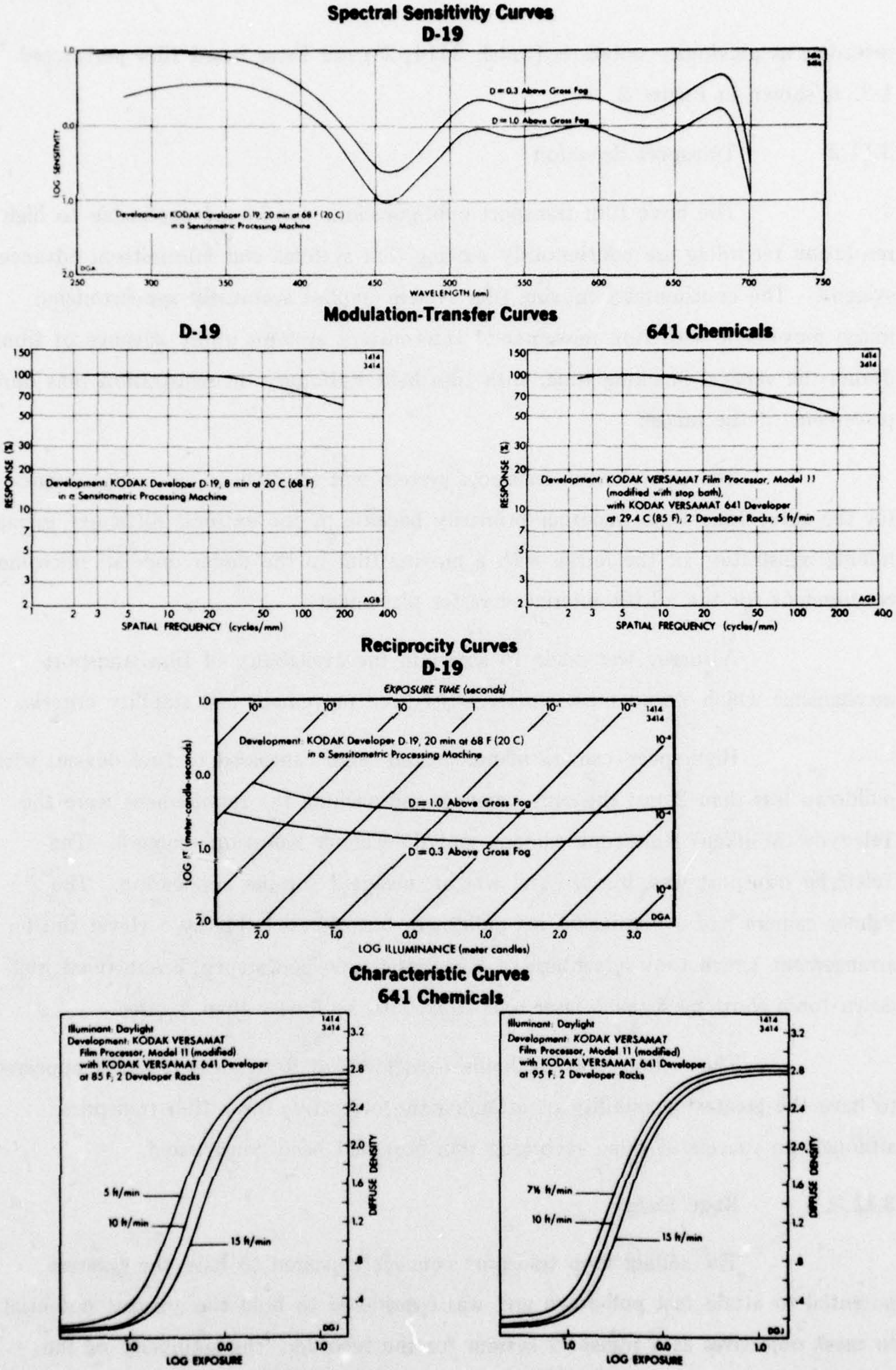


Figure 56 Kodak 3414 Performance Data

recorder, as previously noted, is Kodak 3414, 2½ mil Estar based film perforated 1-3, as shown in Figure 2.

3.11.2 Transport Selection

The basic film transport configurations considered applicable to high resolution recording are continuously moving film systems and intermittent advance systems. The continuously moving film system implies accurately synchronizing image movement with film movement. Intermittent systems imply advance of film during the vertical blanking time, with film held stationary on registration pins during placement of the image.

The intermittent transport system was selected as most appropriate for the video laser beam recorder primarily because of the extreme difficulty in maintaining registration of the image with a moving film to the under one-half micrometer requirement for the VLBR interlaced raster placement.

A survey was made to ascertain the availability of film transport mechanisms which would most closely satisfy the movement and stability criteria.

High speed camera manufacturers were canvassed to find devices with pulldown less than 2 ms; the only cameras approaching the requirement were the Teledyne (Milliken) Kinescope camera, and the Palmer Kinescope camera. The Teledyne transport was, by size and weight, unsuited for the application. The Palmer camera had a nominal 4 ms pulldown, but effected this by a clever shutter arrangement which took advantage of Kinescope tube persistence; unshuttered pulldown for a short persistence laser scan looked to be longer than 4 msec.

The rolling loop mechanism disclosed in References 3 and 4 appeared to have the greatest possibility of attaining the objectives for a film transport, although no successful video recording transport had been constructed.

3.11.3 Basic Design

The rolling loop transport concept appeared to have the greatest potential to attain fast pull-down and was considered to hold the greatest potential to meet objectives as a transport system for the recorder. The simplicity of the

rolling loop concept is best illustrated by the detail of Figure 57. A drum with film loop spaces, or gaps, around the periphery of the drum rotates at a speed such that the gaps reach the projection axis, or gate position, at intervals corresponding to the frame rate. The input sprocket feeds film into the space between the stationary rails and the drum. In the process of advancing between the film input position of the stationary shoe and the gate, the film is accumulated in the gap in a shallow loop in which, at the gate, the total length of film is one pitch plus the gap length. The film is held stationary on registration pins in the gate, but as the loop approaches the gate position, the action of the loop lifts the film off the registration pin, and advances the film one perforation. As the gap passes over the second registration pin, the lower perforation of the frame lays onto the second registration pin. As the drum continues to carry the loop past the gate, the loop diminshes and is passed out of the space between the drum and the stator shoe by means of an output sprocket running at constant speed.

A transfer time of 1.25 ms positions film to accept 100% of the video transmission; 2 ms allows recording of 95% of the frame; 3 ms allows 88%. The interframe transfer time, or pulldown time, is the elapsed time between the first lift of the film at the gate by the lead rotor roller, and the placement of the second perforation on the second registration pin by the trailing roller.

The design postulated as a practical compromise of loop proportions, gap velocities, registration pin separation, and physical size produced a configuration with the following design parameters:

Rotor gaps	2
Rotor diameter	5.920"
Rotor speed	15 r.p.s.
Rotor velocity	279 in/sec.
Rotor gap length	.330"

Due to the low column stability of the thin-base film, it was felt that registration would best be accomplished by locating the main registration pin at the frame in the gap. By the criteria for pulldown time stated above, the second registration pin should be as close to the primary pin as possible - or one perforation

downstream. From the geometry of the rotor and gap combination shown in Figure 58, the total rotor travel to register the film is .580". At the rotor velocity of 279" per second, transfer time is 2.08 milliseconds.

A transport breadboard was constructed to provide experimental data on various aspects of the rolling loop mechanism as a high resolution video recorder camera. Film movement and transfer in the recording gate were studied in depth, and the conclusion reached that registration in the center perforation of the 1-3 perforated film yielded the greatest film stability.

Also observed was a longitudinal reversal of movement of the film in the gate brought about by varying compressive forces exerted by the continually changing feed and ejection loop. When the rotor gap first picks up the loop at the injection sprocket, the longitudinal force exerted by the shallow loop is high. At the same time, the ejection loop at the gate is large and exerts little back pressure. The 12 gram force of the newly formed injection loop deforms the film on the registration pin, at the rate of 11 μ in. (.28 μm) per gram of force; in fact, the travel of film during the cycle was observed to be 134 μ in (3.4 μm). At the point when the ejection loop was shallow and the injection loop full, the force and travel was reversed.

During the breadboard stage, the critical film injection angle was established, the ejection sprocket and path eliminated, and a vacuum gate platen was secondary registration pins added to stabilize film at the gate.

The method used to establish film movement during different parts of the cycle was quantitatively to obtain the degeneration in resolution on film of high resolution targets, double exposed by high speed strobe flash at the start and at varying points of the loop gap in the cycle. By comparing the double-exposed resolution chart to the chart recorded by single exposure, an estimate of film travel between any two points of the cycle was ascertained.

Notably lacking during the period of development of the transport was the equipment to produce a high resolution video raster for recording. The electronic, optical, and mechanical systems were concurrently under development with the transport.

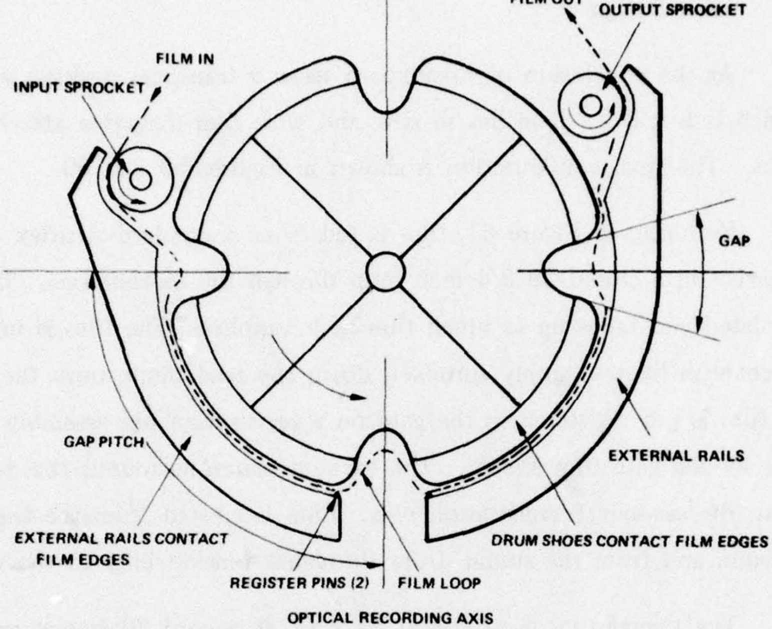


Figure 57 Rolling Loop Transport Mechanism

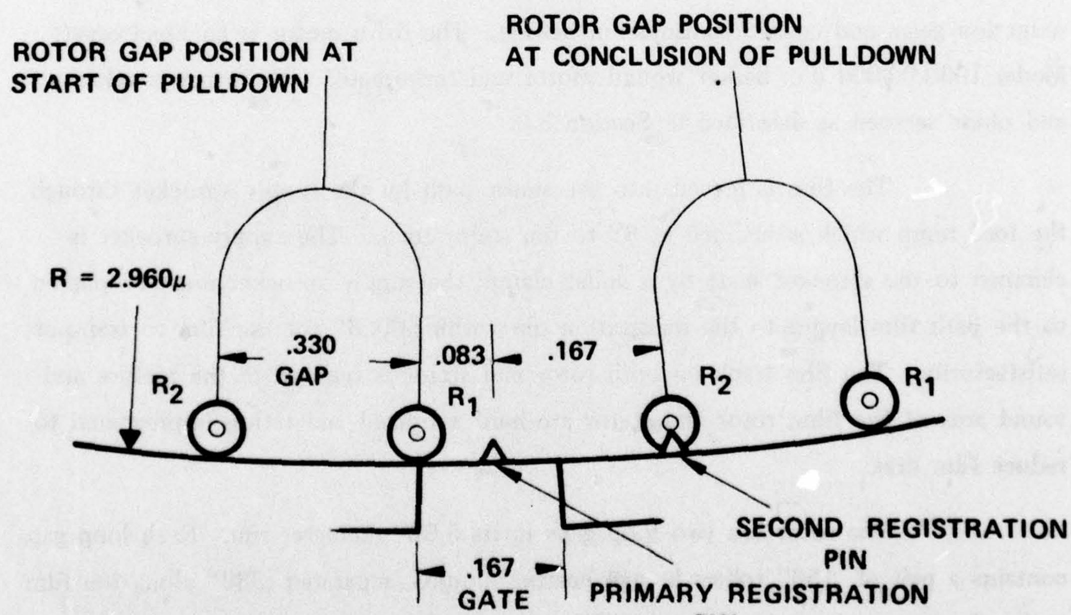


Figure 58 Rotor and Gap Geometry

3.11.4 Final Design

At the conclusion of breadboard tests, a transport package was designed which is 8 x 8½ x 9 inches in size, and with film magazine attached, weighs 20 lbs. The final configuration is shown in Figures 59 and 60.

Referring to Figure 61, film is fed from a standard Arriflex 400 ft. 16 mm magazine in a closed 28 3/4 inch loop through the mechanisms. The magazine is articulated and takes up as much film as it supplies. The film is injected into the mechanism by the supply sprocket, down the feed ramp, onto the stator track. The film is pin registered in the gate on a registration pin assembly which is retractable by the gate film keeper. The vacuum platen surrounds the gate and extends up to the secondary registration pins. Film is ejected from the track to the sound drum, and from the sound drum through a tension idler to the magazine.

The two-gap rotor rotates at 15 r.p.s. to record 30 frames per second. The rotor is rigidly mounted to the drive motor shaft, from which all mechanical support devices are geared. The 18 tooth supply sprocket rotates at 1/9 the speed of the rotor. The film magazine and sound drum are driven through reduction gears and cogged transmission belting. The drive motor is an Electrocraft Model 1030-00-004 d.c. basket wound motor and tachometer. The rotor is velocity and phase servoed as described in Section 3.6.

The film is forced into the stator path by the supply sprocket through the feed ramp which is inclined at 8^{o} to the stator track. The supply sprocket is clamped to the sprocket shaft by a collet clamp; the supply sprocket must be phased to the path film length to the registration pin within .0008" for the film to transport satisfactorily. The film track on both rotor and stator is relieved in the picture and sound area of the film; rotor and stator are hard anodized and teflon impregnated to reduce film drag.

The rotor has two loop gaps in its 5.92" diameter rim. Each loop gap contains a pair of .156" rollers in ball bearing mounts, separated .330" along the film path. Rotor to stator clearance is .006", roller to stator clearance is .004". Magnetic steel pins in two rotor spokes serve as triggers for the magnetic detectors in the housing used for position servo signal.

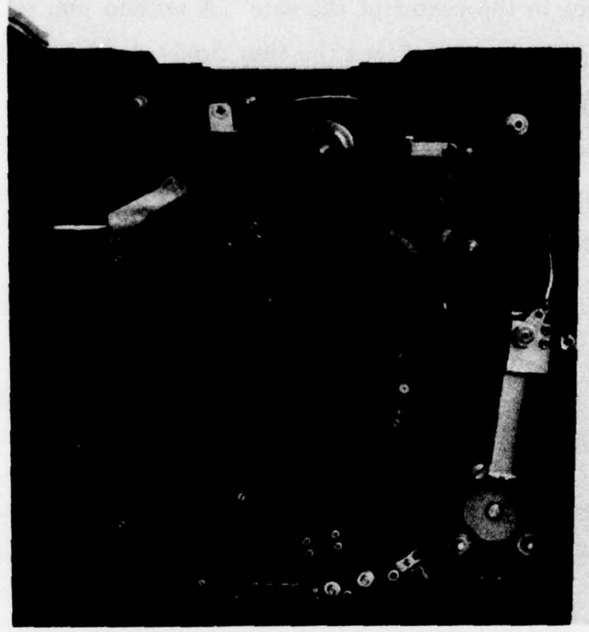


Figure 59 Rolling Loop Transport, Front View

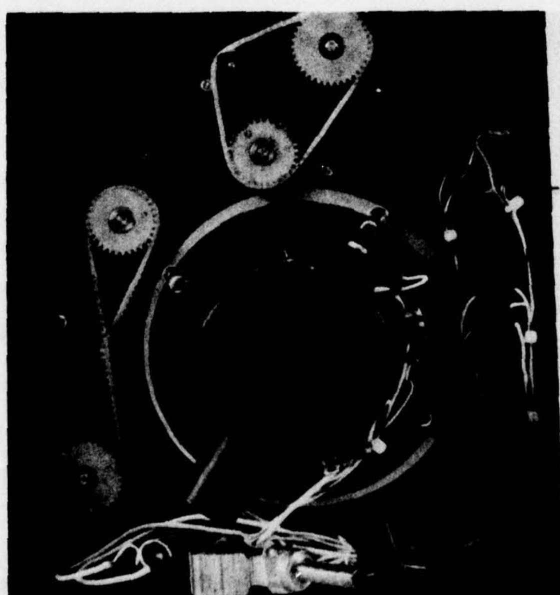


Figure 60 Transport - Rear View

In the gate area, the primary registration pin registers the center row of film perforations in the center of the gate. A tension pin, set one pitch behind the primary registration pin, keeps the film firmly against the registration pin. A vacuum platen, in which a vacuum of 20" H_2O is maintained, aids in providing column stiffness and stability to the film in the gate area. At the end of the vacuum platen, two secondary registration pins prevent the loop ejection reaction from disturbing the film in the gate.

The sound drum is driven in synchronism with the rotor through reduction gearing and gear belt. Variable density optical sound is recorded on the film on the drum by a dual channel audio signal modulated light emitting diode projector assembly, described in Section 3.12.

The film magazine is a standard Arriflex 400 ft. film magazine modified to pass Super-8 mm film. The magazine holds 1000 ft. of 2½ mil film on 2" cores.

3.11.5 Performance

The pin registered transport showed a 2.0 to 2.1 millisecond pulldown. Jump (vertical frame jitter) is .0005" max. with a typical jump of under .0003". Weave (horizontal frame jitter) is .0008" max. with .0005"-.0006" typical. Jump and weave was determined by exposing a calibration target on film twice on successive runs. This is an indication of frame steadiness, but does not accurately provide data on the amount of movement of the film during exposure.

It was consistently noted that, to attain moderately acceptable pictures, the film feed sprocket must feed film to the gate so that, upon transfer of the frame by the loop, the perforation must land within .0008" (20 μm) of the leading edge of the registration pin. Any departure from a 0 - .0008" mismatch of perforation and registration pin results in a visible discontinuity in the final picture, and a moire effect produced by irrugular twinning of raster lines.

The chief contributor to the misregistration problem is ambient humidity variation. Estar based film has a humidity coefficient of expansion of .0033% relative humidity change. Over the 9.3" feed path length of the transport, a 10% RH change can produce a length variation of film, hence misregistration, of

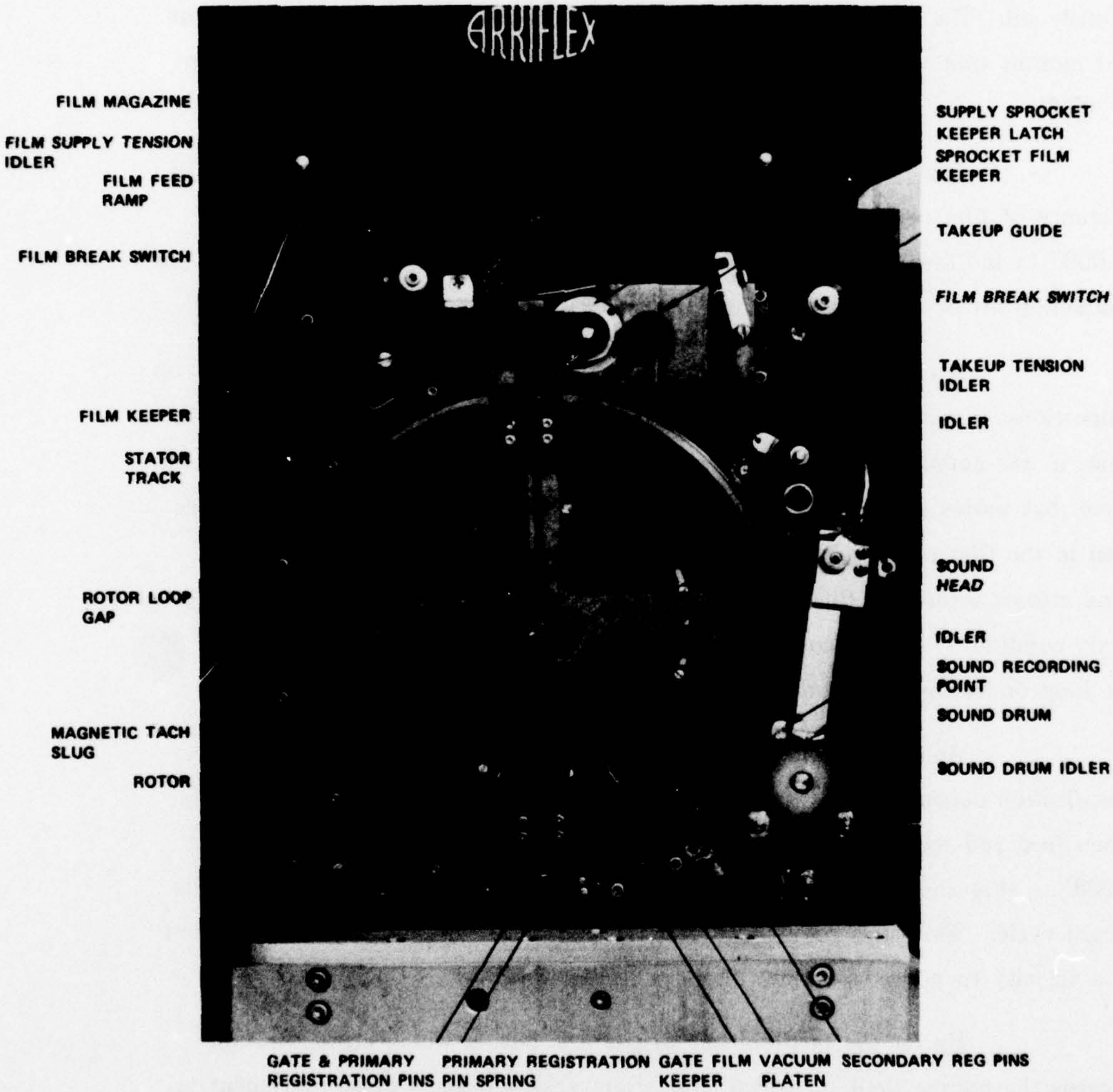


Figure 61 Transport

.003". Similarly, a temperature coefficient of expansion of .002% per degree centigrade produces a .002" length change over 10^{o}C; however, the temperature coefficient closely approximates that the aluminum alloy structure, so the temperature effect is virtually nil. The humidity condition, however, is very apparent; over a period of two months time, relative humidity changes of 40% produced misregistrations up to .008".

The problem is further emphasized by the fact that the commercial tolerance of film perforation placement is ± .017" per hundred perforation or ± .009" in the feed path length. Generally speaking perforation spacing within one production lot of film is uniform over the feed path length within .001".

A condition noted during testing indicates that the combination loop proportions, film stiffness, and gap velocity may be approaching a limiting condition. First, it was noted that the perforated film does not move in the loop in a smooth curve, but moves in strained segments, deflecting more acutely at the perforations than in the film between the perfs. The film from the mechanism shows slight bend creases across the film at either end of the perforation, indicating a yield point strain condition. Such a condition can, and occasionally did, lead to a collapse of the loop under the rollers, resulting in a foldover jam.

As a general statement, the degree of conformance to performance specification depends almost entirely on the feed sprocket-registration relationship. When feed and registration place the perforation onto the registration pin within .0008", a slippage closely conforming to the 134 μ in. proceeds during the whole record cycle. When this occurs, the vertical scanner can be programmed to record at a velocity to permit excellent interlace registration.

By far the predominant situation is one in which misregistration exceeds the narrow limit, in which case, strain energy releases cause movement up to .002" in an unpredictable pattern, which precludes correction by the vertical scanner.

3.12 Audio Recording System

The audio recording system records two channels of variable density optical sound track located on the film as shown in Figure 2. The dual channel, light emitting diode driven writing head is located approximately 5.5 inches, or 33 frames, downstream from the gate, as shown in Figure 62.

3.12.1 Audio Amplifiers

A two channel audio system has been provided in this system as shown in Figure 63. Each channel has a balanced input with an impedance of 5 kilohms. The amplifier section provides a 25 dB of automatic gain control. The AGC has an attack time of 100 msec. and a decay time of 4 seconds. Frequency pre-emphasis has been employed to ensure audio response to 5 kHz. Independent controls of depth of modulation and film exposure level from the LED exposure source have been provided. The audio amplifier chassis mounted in the electronic card cage in location AO1-6.

3.12.2 Recording Head

The recording head contains the optics and light emitting diodes to record two separate sound tracks on the moving film. The light emitting diodes, set at a bias level of approximately .9A, are intensity modulated by the audio frequency signal to produce the variable density sound track. The radiating L.E.D. is imaged through an 8 mm f.1. spherical and a 2 mm f.1. cylindrical lens to produce an audio modulated slit image on film. Recording is done on the flywheel stabilized sound drum to maintain uniform focal distance during recording. The optical diagram of the recording head is shown in Figure 64.

The light emitting diodes are Monsanto MV4-H, radiating 2 mw at 670 nm with a current of 1.0 amp. Radiation intensity is linear with input current. The radiant area is 2.5 by 2.5 mm in size. The L.E.D. lenses have been ground down to a flat surface to provide nearly lambertian radiation to the system.

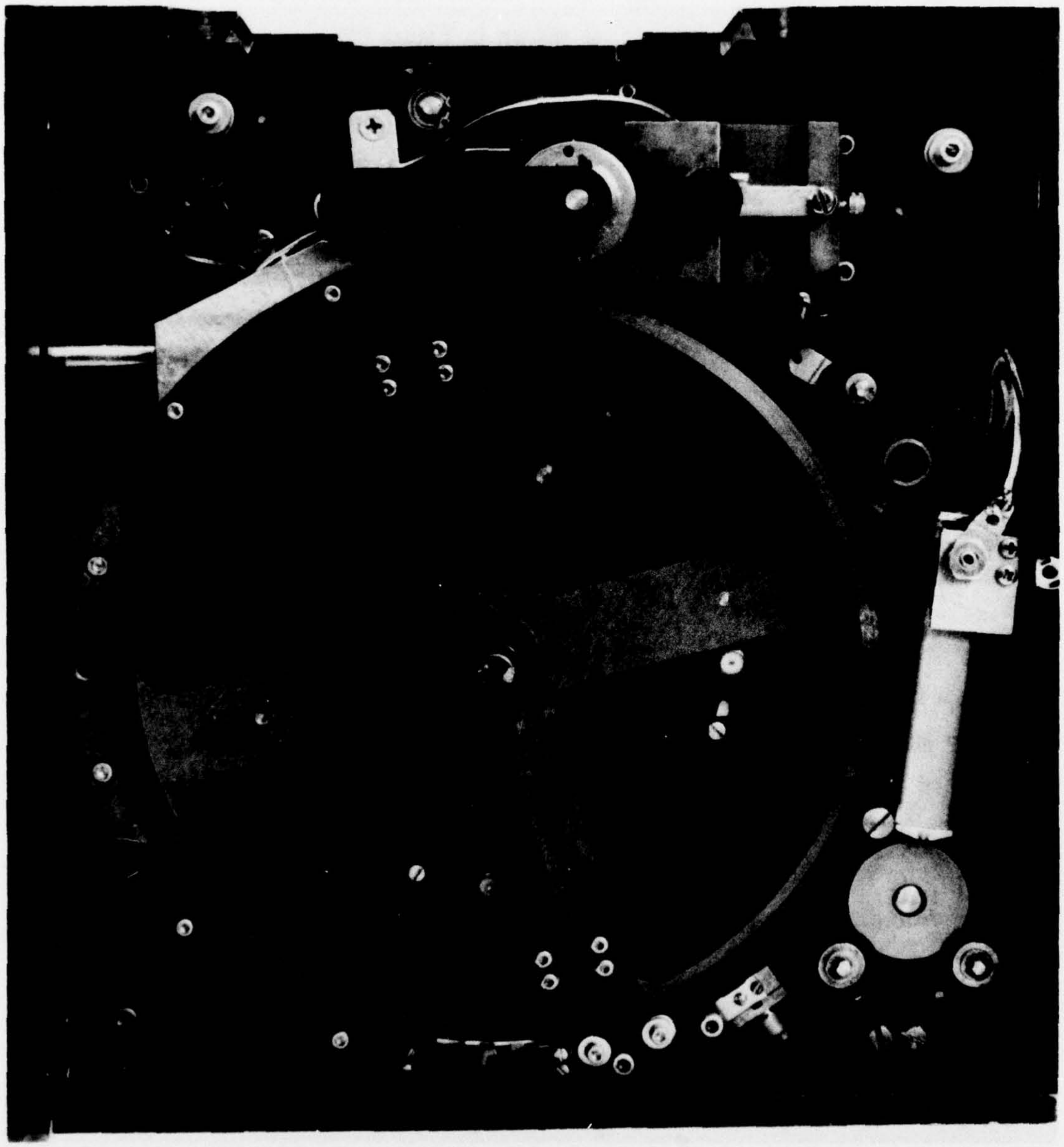


Figure 62 Record Head Location

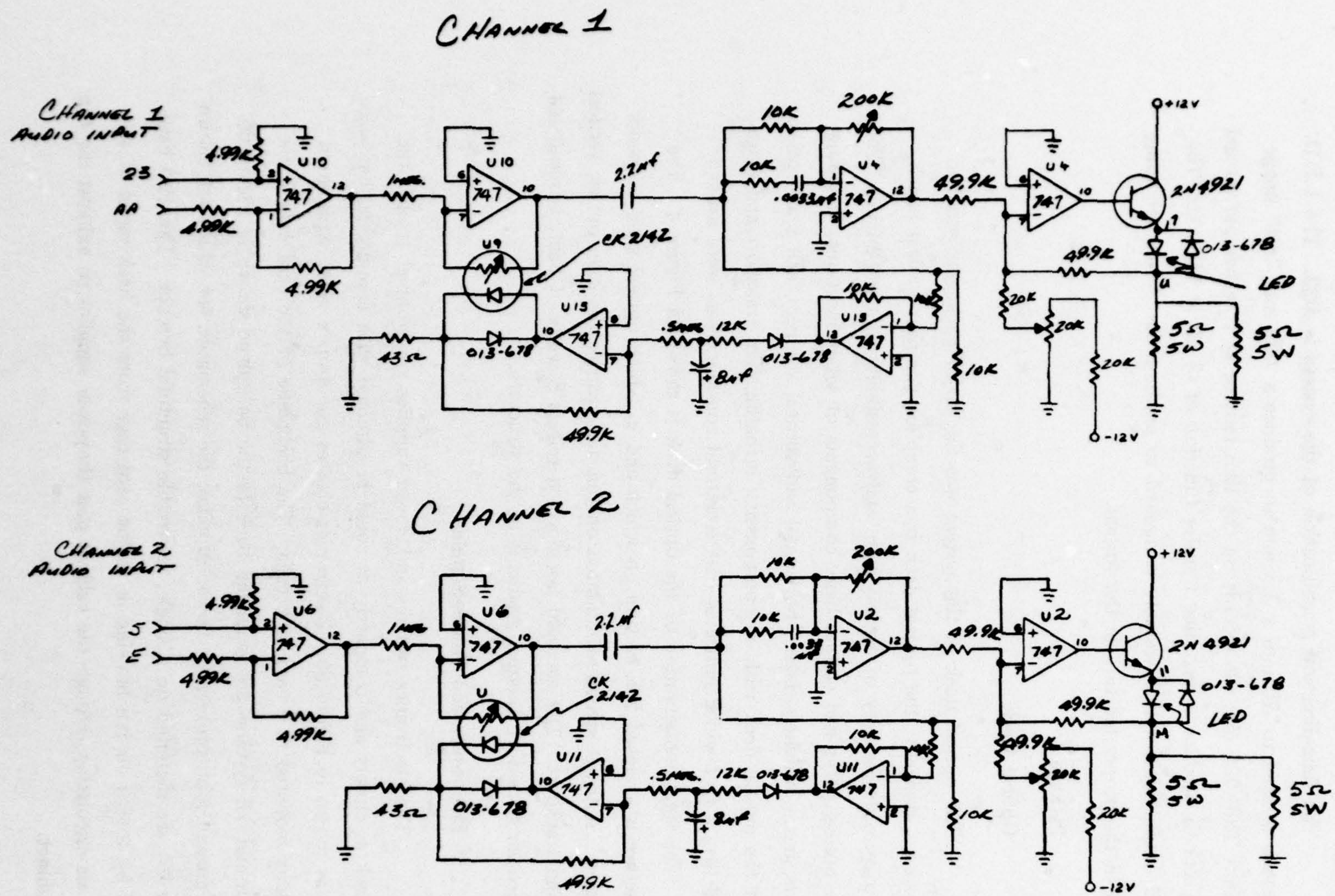


Figure 63 Audio Amplifiers Schematic

The time-direction magnification of the system is .022. The L.E.D. radiant area is masked to .75 mm x 2.5 mm to produce a .025 mm "slit" image on the film. The .025 mm slit records on the film moving at 5 inches per second (127 mm/sec) to produce a recording transfer function of -3 dB at 2500 Hz. The cylindrical output lens of the assembly is masked to produce the .5 mm recording slit width in the proper location in the format.

3.13 Package

3.13.1 Optical Deck

The optical deck of the system was the major packaging problem of the system. Basically, the optical deck is a complex, compact optical bench, required to provide stability of optical path, and accessibility of components. The 2.5 meter optical paths had certain basic components of set proportions, including modulators, beam switchers, lasers, horizontal and vertical scanners, and scan optics. Weight of the optical deck with all components, including film transport and magazine is 66 lbs., a fact which indicates that structural considerations were a major problem. The final configuration of the optical deck is shown in Figure 4. The deck structure is a closed box section on which and in which optical train elements are mounted. A tower structure mounted on the deck carries the scan optics, vertical scanner and transport. The enclosed laser, which rejects 8 watts of heat, is ventilated with forced air to reduce thermal gradients in the structure.

3.13.2 Electronics and Power Supplies

The electronics systems and power supplies are grouped around the optical deck as closely and compactly as could be attained with commercial hardware elements as shown in Figure 65. Electronics chasses are Ampex video equipment chassis cards mounted in a card rack cage. The backplane of the card cage is the system ground; all systems are grounded back to the backplane shown in Figure 66 to avoid ground loop problems. Power supplies, the schematics for which are shown in Figure 67, are mounted on a single, removable structural bracket. The card cage is cooled by forced air fan blowing in to the card cage from the back panel of the housing, air circulating through the cabinet past the power supplies to exhaust the top of the cabinet.

3.13.3 Auxiliaries

A vacuum blower to provide a .5 cfm of 20" H_2O vacuum for the film transport vacuum platen is powered by a 400 Hz., 117 v.a.c. 1/10 HP induction motor.

Forced air of approximately 6 cfm at .3" H_2O is provided by a miniature brushless d.c. motorized centrifugal fan.

Cabinet cooling is provided by a 400 Hz., 117 v.a.c. propeller fan circulating 100 cfm of air through the electronics spaces.

A Hobbs hour meter registers total time during which the recorder is in "Standby" or higher operational status.

3.13.4 Frame and Enclosure

A welded tubular aluminum frame carries all components and mounts the enclosure cabinet. The optical deck is isolated from the frame structure by soft multiplane vibration mounts, with sufficient constraint to operate in a horizontal or vertical position. All enclosure panels are removable for maintenance, but the major working access is through the front and rear of the enclosure. The optical deck can be removed through bottom of the frame.

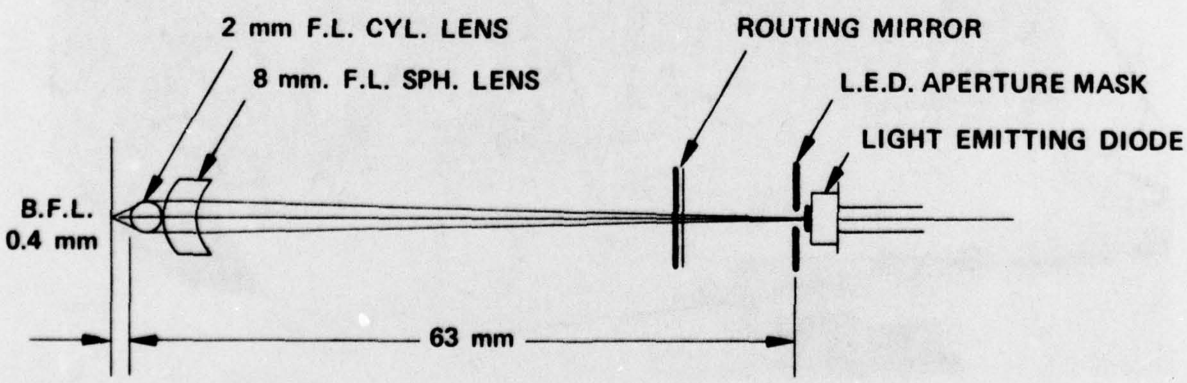


Figure 64 Record Head Diagram

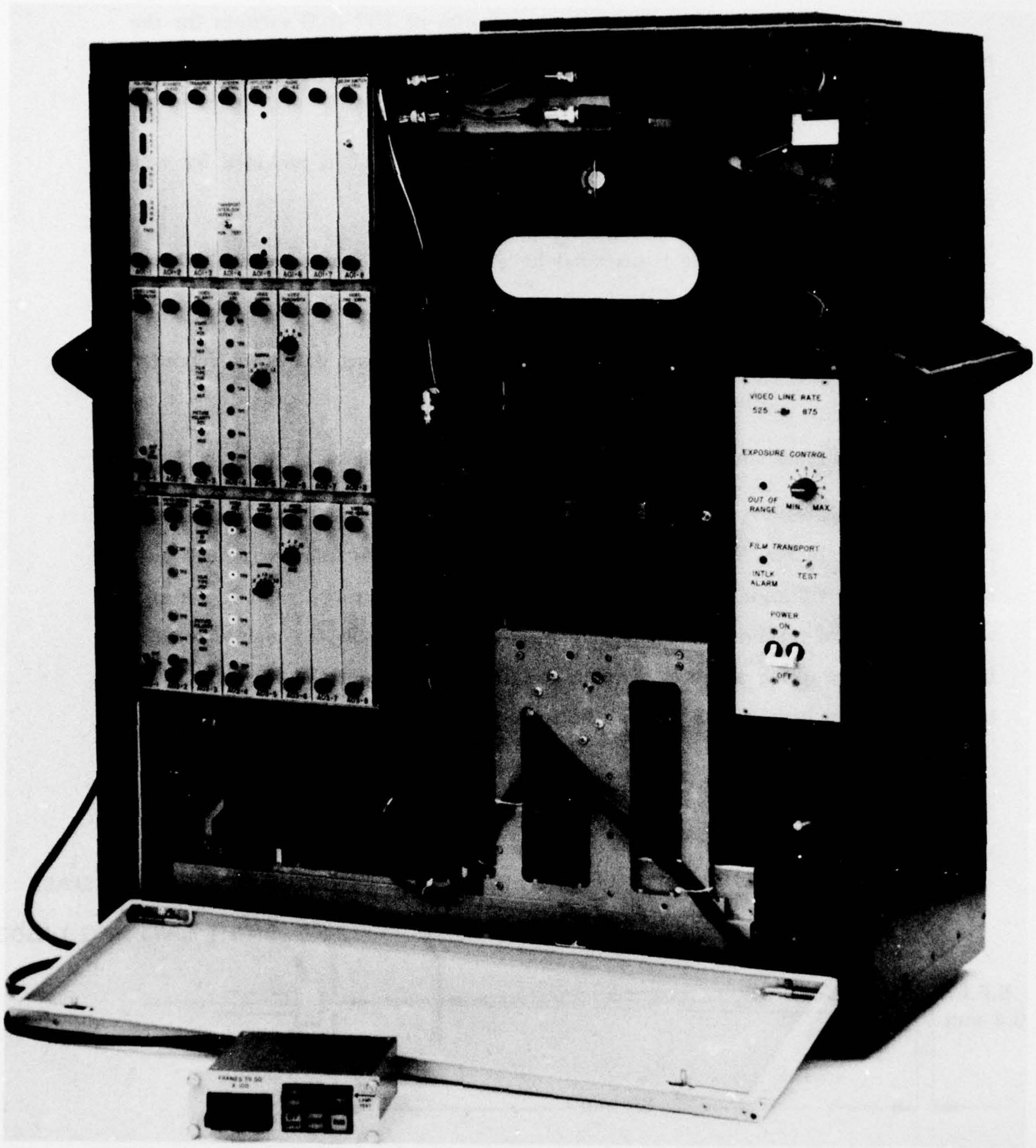


Figure 65 Subsystem Packaging Arrangement

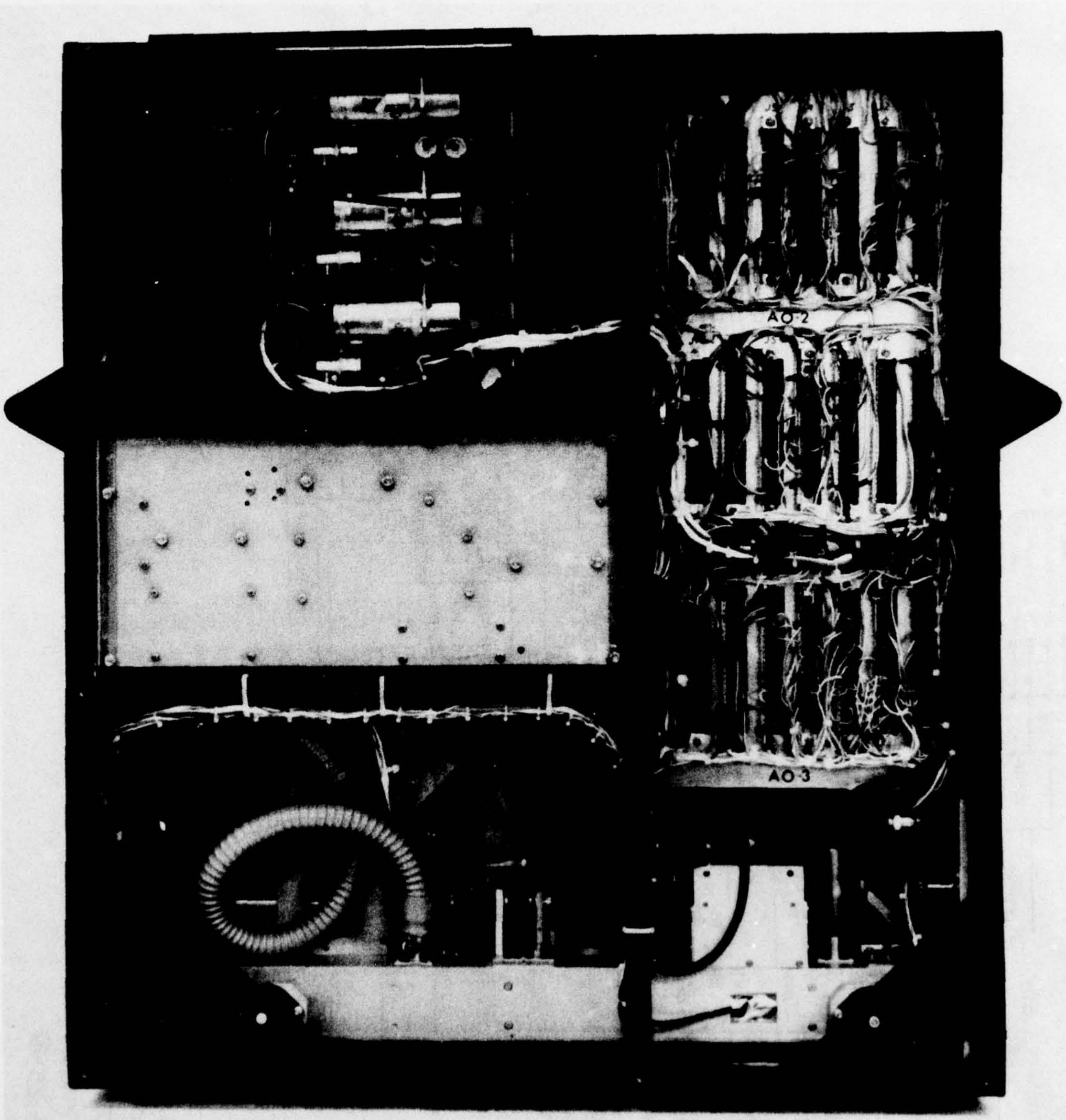


Figure 66 Card Cage Back Plane & Power Supplies

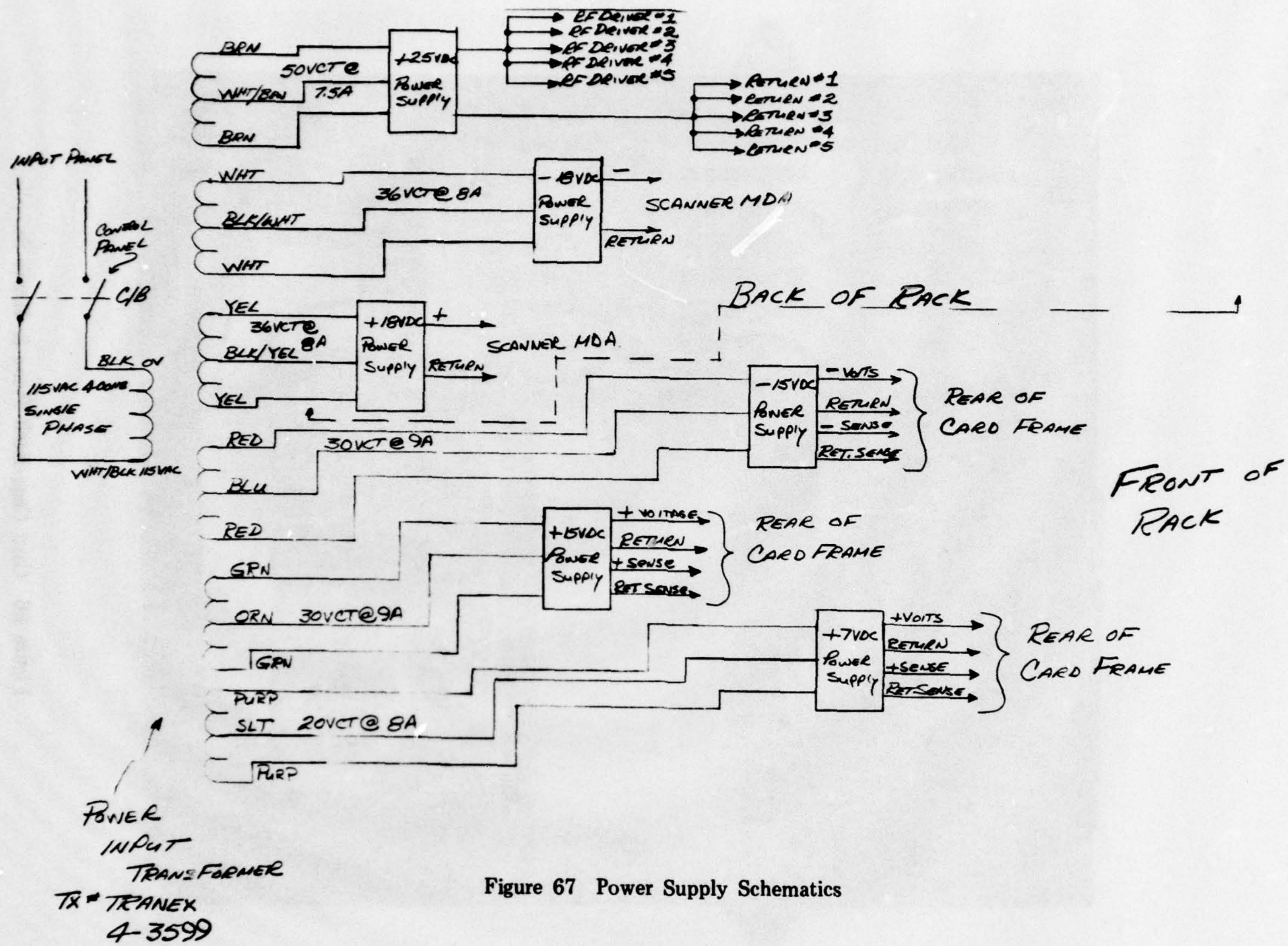


Figure 67 Power Supply Schematics

SECTION IV
SYSTEM PERFORMANCE

The performance of subsystem designs has been discussed in Section 3. The overall performance on the contract Statement of Work items is summarized in Section 4.1. As indicated in Section 3.0, the performance of the rolling loop film transport tends to seriously degrade the extremely high resolution picture scanned onto the film. To assess the true merit of the system, it is, therefore, appropriate to discuss the electronics/optics system performance up to the film, as well as total system performance.

4.1 Performance Summary, Statement of Work Items

The following is summary of the Statement of Work specification, and a statement of compliance or variance. Performance items are discussed in detail in Section 4.2 and 4.3. following.

S.O.W. Para.		
4.2.1	30 Frames per second	Comply
4.2.3.1	Power: 400 watts, max.	750 W.
4.2.3.3	Power standards: cat. C power	Comply
4.2.3.4	Isolations: both sides of power input isolated from chassis ground	Comply
4.2.4	Warmup: 5 min.	Comply
4.2.5	Video in: 2 EIA signals, 525 or 875 line video	Comply
4.2.5.1	Input impedance: 50, 75, 92 Ω,	Comply

4.2.6.2	Audio signal 0-5 v w/agc	Comply
4.2.7.1	Auto run: 3000 Ω impedance, non-reactive both sides isolated from chassis	Comply
4.2.7.2	Auto run signal: 3-32 v, 10 μs to 20 ms, 50-1000 μs risetime	Comply
4.2.8	Film 2R1667 (1-3), Single channel op. a design goal	Dual Channel Only
4.2.10	Frame rate: 30 frames, 60 fields/sec.	Comply
4.2.11	Audio - ANSI Stds.	33 Fr. Separation
4.2.12	Film Supply - 2 hours, 220,000 frames/track (1414 film) or 75 min., 130,000 for 3414 film.	1000 Ft., 3414 Film 72000 frames
4.2.13.1	Remote control: 5" Dzus rail panel, panel height under 1.5"	2.0" Hgt.
4.2.17	Packaging, dimensions - 8" x 18" x 36"	12.75" x 32.75" x 29.1"
4.2.18	Broken film detector	Comply
4.2.19	Elapsed time indicator	Comply
4.3.1	Control panel detail	
4.2.9	Format ANSI Ph 22.157	.212" x .158"
4.3.14	Frame counter: self illuminated, count-down, reset	Comply except not illuminated
4.3.15	Size of control panel 1.5" x 5.72"	2.0" Hgt.
4.3.16	Control panel weight 2.5 lb.	Comply
4.3.2	Power supplies: no external breakers	Comply
4.3.5	E.O. components	Comply

4.3.5.1	Laser: ruggedized, wavelength optional	Comply
4.3.5.2	Bias control: *intensity control*	Comply
4.3.5.4	Modulators - two channels	Comply
4.3.5.4.1	Gamma control: 4 steps 1.0 to 1.5	Comply
4.3.5.4.2	Picture polarity reversal	Comply
4.3.5.5	Simultaneous line scan	Comply
4.3.5.5.1	Scan motor: brushless d.c., multi-face polygon; 30 watts max.; 30 sec. runup time	Comply
4.3.5.5.2	Optical tack sensor	*Hall El. Sense*
4.3.5.6	Optics - Bouwer-Maksutov	Comply
4.3.5.6.1	Distortion mask	None
4.3.5.7	Raster scan: electromech deflector	Comply
4.3.5.7.1	Raster scan rate: 60 fields/sec., 2/1 *interlace*, 2.5 ms flyback	Comply 1.3 ms Flyback
4.3.6.1	Pulldown time 2.5 ms, max.	2.1 ms. pulldown
4.3.7	Test gate: replaceable test gate	Gate viewer
4.4	Image Performance	-
4.4.1	Frequency response: 16 MHz ± 0.5 dB	Comply
4.4.2	Variable bandwidth: 2, 4, 8, 12 MHz	Comply
4.4.3	Spatial frequency response: 500 cy/line, MTF (scan) 50% Vertical 785 & 480 lines MTF = 50% w/squarewave inputs	Electro-optics Comply; Film Image Sub-spec.

	Rolloff 5% center to edge	Electro-optics complies; film 10% rolloff
4.4.4	Contrast ratio: 200/1	$\triangle$Density 2.3
4.4.5.1	Shading: large area flat to 2%	$\triangle D_{1.0} = .03$
4.4.5.2	Shading: local, ± .005 density units	$\triangle D_{1.0} = .05$
4.4.6	Synchronization: input 100 ns jitter max.	Comply
4.4.6.1	Line position accuracy: start each scan ± 4 spot diameters	Electro-optics comply; Film image sub-spec.
4.4.6.2	Line to line deviation: 0.5 spot diameter	Electro-optics comply; Film image sub-spec.
4.4.6.3	Max. deviation from average start under 1 spot diameter	Not Measured
4.4.6.4	Line position & spacing: no degraded image, bunching, discontinuities	Electro-optics Complies; Film shows movement
4.4.7	Gray scale: 15 step IEEE gray levels, no ringing	10 steps
4.4.8	Raster: ANSI PH 22.157, ± 0.1 mm, square to $1/3^{\circ}$	.212 x .158 (Undersize)
4.4.9	Raster steadiness: variation in placement not over 12 μ (.0005") jump and weave under 25μ (.001)	Comply
4.4.10	Raster linearity: ± 1% distortion	Comply
4.4.11	Raster line content	2.1 ms pulldown - 95% max line content
4.4.12	Spot geometry control: spot size change for 875/525 lines	None

4.4.13	Contrast enhancement, expand, compress, selectivity, amplify	Comply
4.5.1	Film load time: under 1 minute	Comply
4.5.2	Setup time: 1 hour per week	Comply
4.5.3	Environment: 10^oC to 60^oC	Comply
4.5.4	Altitude: to 10,000 ft.	Comply
4.5.6	Size: under 3.0 cu. ft.	7 Cft.
4.5.7	Weight: 120 lbs. max.	226 lb.
4.7	Test and evaluation: based primarily on film results; may use electronic measuring and detecting to support evaluation.	Electro-optics Sys. Complies; Film Images Sub-spec.

4.2 Electronics/Optics System Performance

Considering the total VLBR system as consisting of two major subsystems, the electronics/optics system, and the film transport system, the performance of the system up to the film verified the feasibility of the laser scanner raster system as a superior wideband, high resolution component. All items pertaining to resolution and bandwidth in the system up to the film were met or exceeded, as observed in the illustrations in Section 4.4.2.

4.2.1 Frequency Response

Statement of Work paragraph 4.4.1 required that frequency response be ± .5 dB to dB to 16 MHz. Modulator optical response was shown in Figure 45. The oscilloscope traces of the video signal through the video electronics system are shown in Figure 68. Variation of under 1 dB (11%) in the gamma corrected signal is observed up to 16 MHz.

The bandwidth limiting filters required in S.O.W. paragraph 4.4.2, permit flat response out to the selected limiting frequencies of 2, 4, and 8 MHz. The oscilloscope traces of Figure 69 indicate the -3 dB point of each filter system.

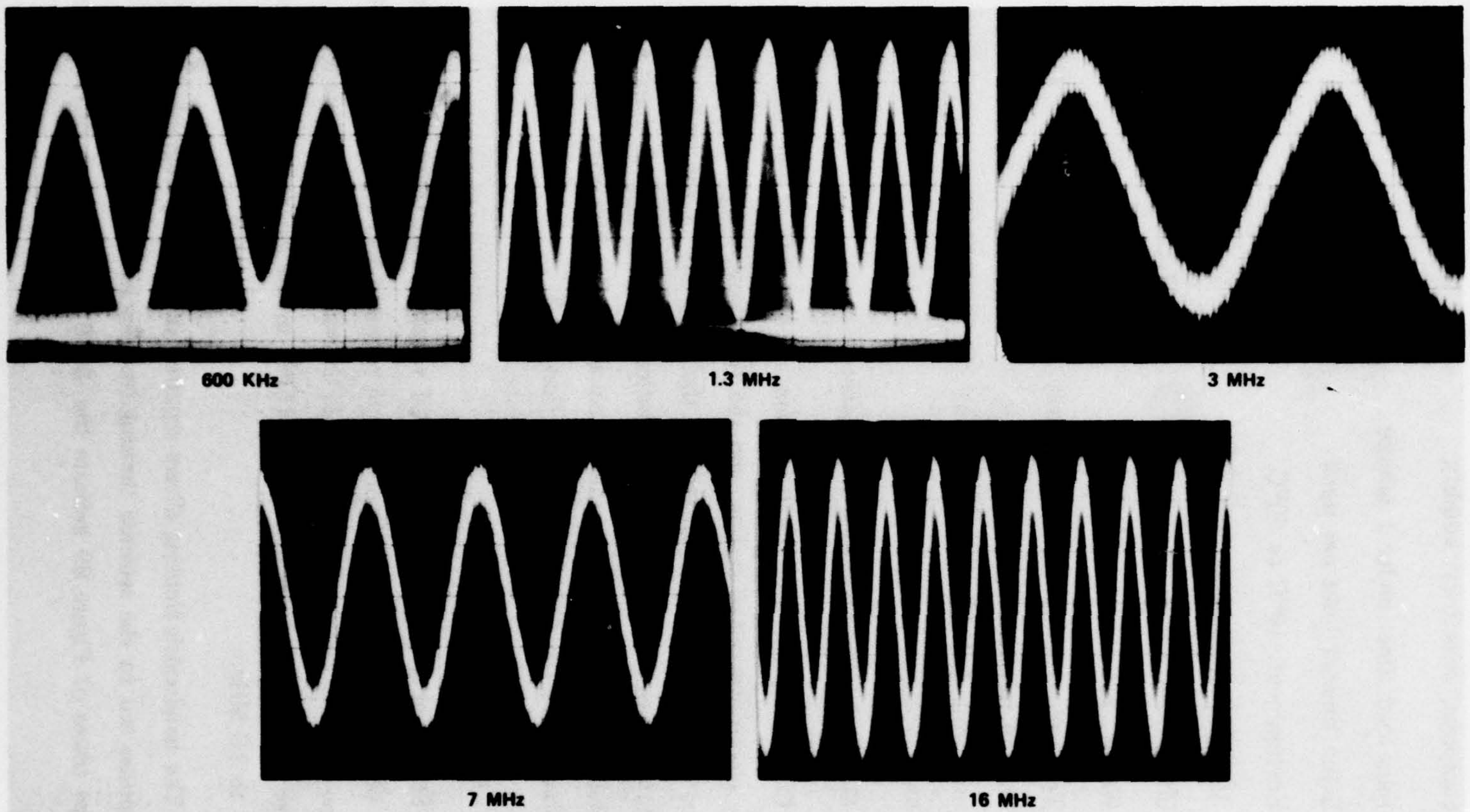


Figure 68 Gamma Corrected Video Response

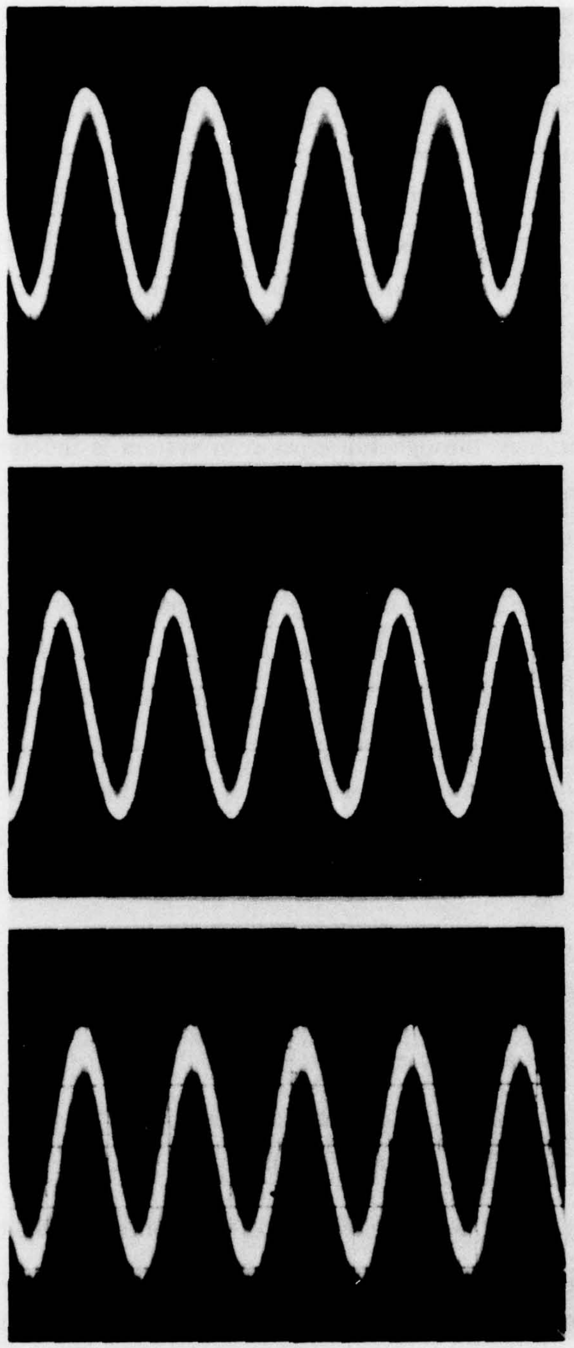


Figure 69 Bandwidth Limiting Filter Response

4.2.2 Spatial Frequency Response

The spatial frequency response of the aerial image is extremely difficult to assess in the VLBR system because of the difference in pupil position and angle of approach of the alternate scan beams noted in Section 3.1.3.9. A system was devised in which a wide angle projection lens with a field lens close to the image plane was used to collect both scan beams at the image plane. The lens projected at approximately 50 X magnification the aerial image onto a Chalnicon tube (a red-sensitive vidicon type sensor) arranged to cross scan to VLBR raster. The Chalnicon camera image was displayed in a 525 line video raster on a monitor tube which then showed the aerial image at approximately 400 X magnification.

The transfer efficiency through the cross scan system is indeterminate, the elements consisting of a projection lens of ordinary quality, the Chalnicon video CCTV Camera of 3 MHz bandwidth, and a standard CRT monitor.

The illustrations of Figure 70 show the throughput quality of the laser recorder with a 525 line test pattern. Figure 70(a) shows the iconoscope pattern applied directly to the monitor. Figure 70(b) shows the areas sampled by the cross scan magnification system. The remaining figures show the quality of the aerial image at the film plane of the signal process through the VLBR. Line spacing is 8.9 μm; approximately 64 lines are visible from corner to corner of the monitor. Deduced from Figure 70, are:

1) Line start, or line to line spot registration is within 0.5 spot diameter.
2) Line spacing does not vary in excess of 0.2 line space.
3) Resolution of 525 line rate is an estimated 380 cycles per line at 70% MTF (Figure 70(c)).

The performance at the 525 line rate is further confirmed by the illustrations of Figure 71 made by the same technique. Resolution of 800 lines at approximately 40% MTF, or 550 cycles per line, is observed in the aerial image in Figure 71(f). Rolloff at the higher frequency is obviously due to the spot size and velocity rather than video chain bandwidth limitation.

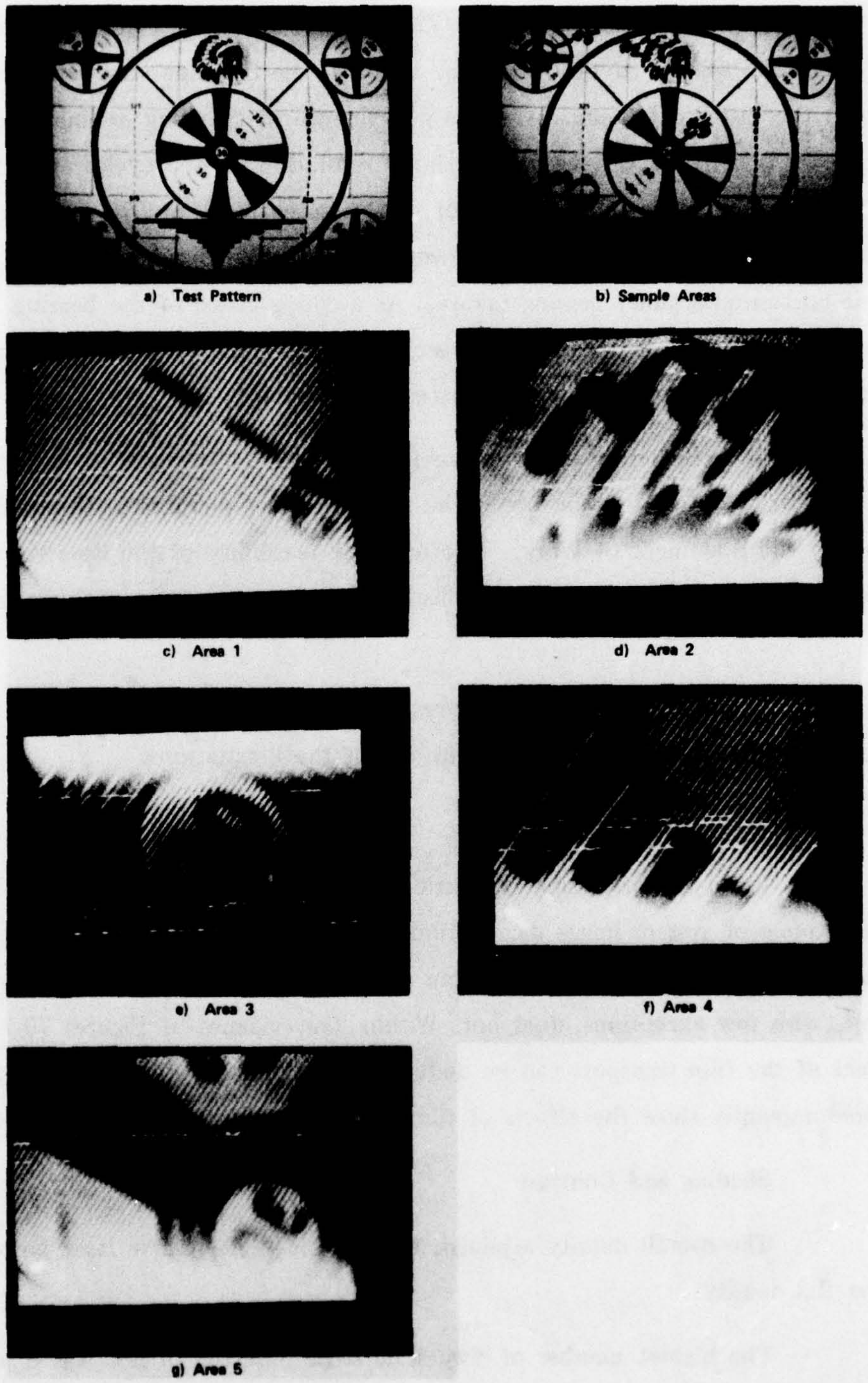


Figure 70 525 Line Cross Scan of 525 Line Per Frame/Iconoscope Test Pattern Throughput - Electronics/optics System

The illustrations of Figure 72 show the throughput quality of the optics/electronics system to the film plane image at the 875 line scan rate. Line spacing of the raster is 5.3 μm. There is no evidence of twinning or line space variation of over 0.2 line space. Figure 72 shows resolution of 475 cycles at an estimated 50% MTF. Figure 73 shows a throughput to the image plane of 670 cycles at an estimated 40% MTF. Line spacing and twinning in Figure 73 were caused by an incipient horizontal scanner bearing failure. As a consequence of the bearing problem, the line starts in Figure 73 appear to vary as much as one spot diameter, and line spacing variations to .35 line space are estimated.

The conclusion to be drawn from Figures 71 through 73 is that the VLBR electronics/optical system, up to the film, produces pictures to the quality required by the Statement of Work. In effect, the feasibility of the laser recorder as a high resolution recording device fulfills the expectations of the analysis and design.

Of singular interest in Figures 70, 71 and 72 is the absence of pronounced cyclical twinning and bunching in any of the illustrations.

4.3 Total System Performance

From the discussion of Section 3.11.5, it was anticipated that the principal source of system image degradation would be the film transport. While the electronics/optics portion of the system performed to specification, the film transport, with few exceptions, does not. Within the evidence of Figures 70-73, the effect of the film transport can be deduced. As a general statement, the test films predominantly show the effects of film misregistration and slip during recording.

4.3.1 Shading and Contrast

The overall density attained, with considerable reserve laser power, was over 2.3 density.

The highest number of gray scale steps observed in test was 8 out of 10 step scale. While the full gray scale was observed at the image plane, probably due to high gamma processing of film, only eight steps are visible on any test film.

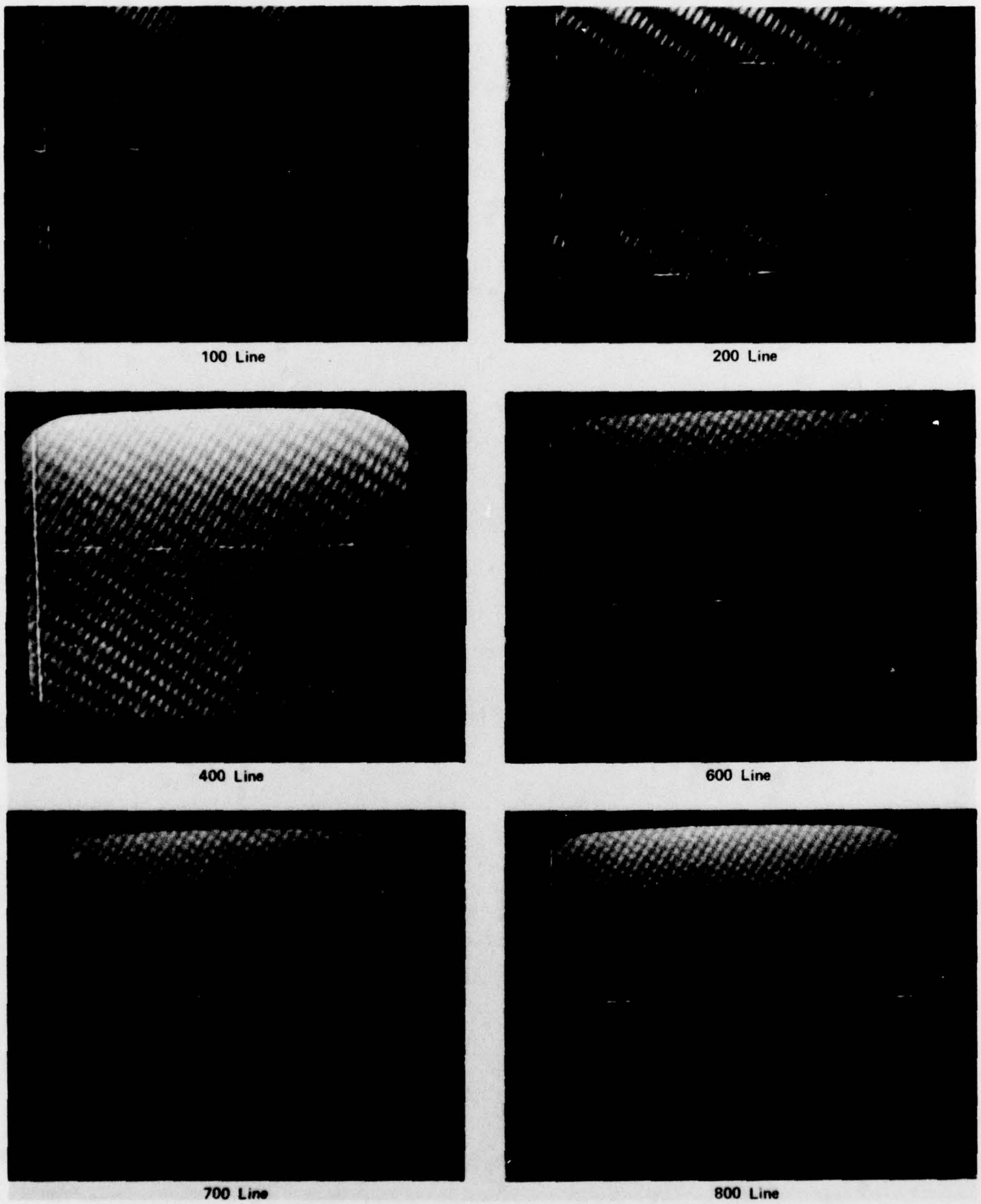


Figure 71 525 Line Cross Scan of 525 Line Per Frame Resolution Pattern Throughput Electronics/Optics System

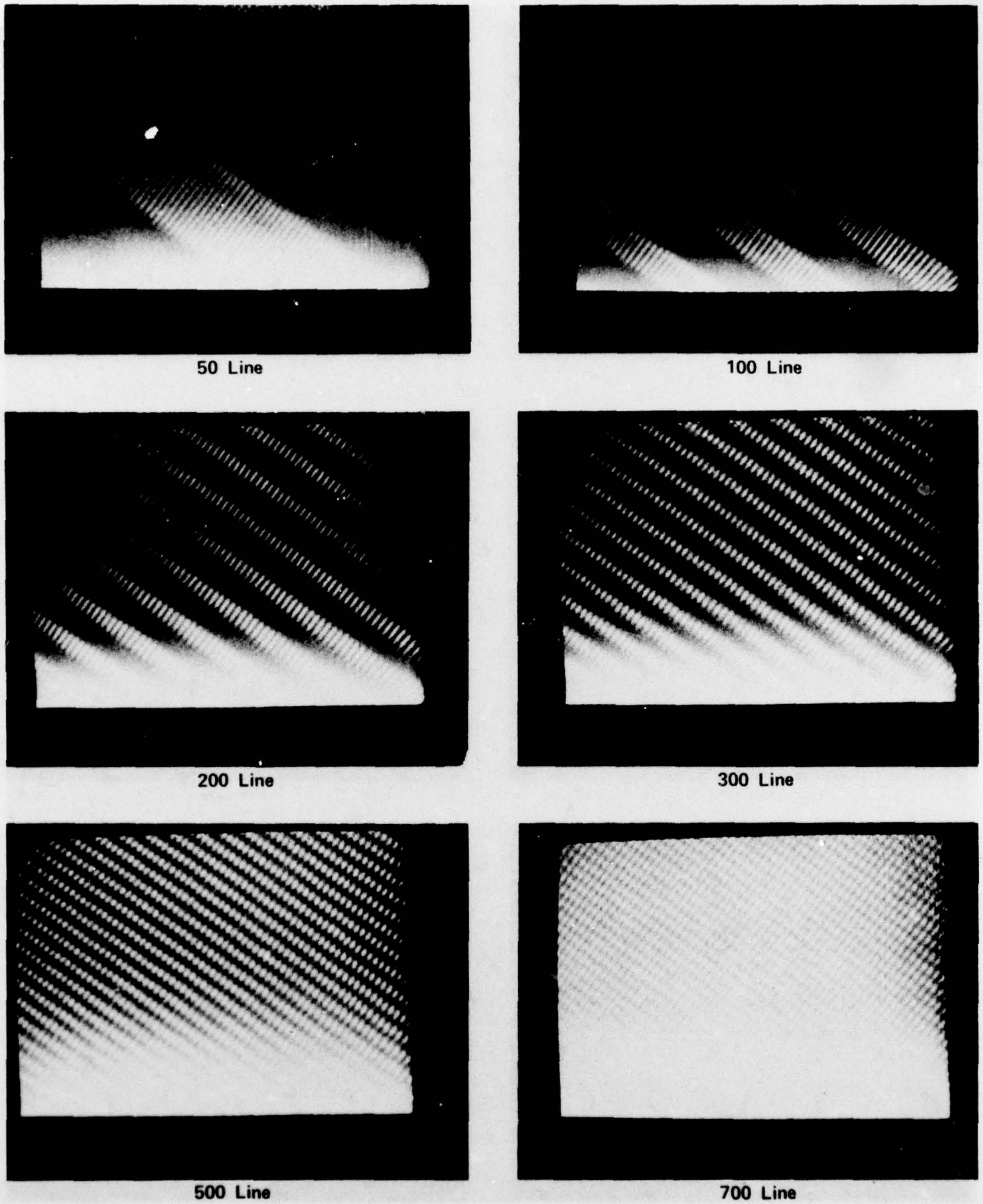


Figure 72 525 Line Cross-Scan of 875 Line Per Frame Resolution Pattern Throughput Electronics/Optics System

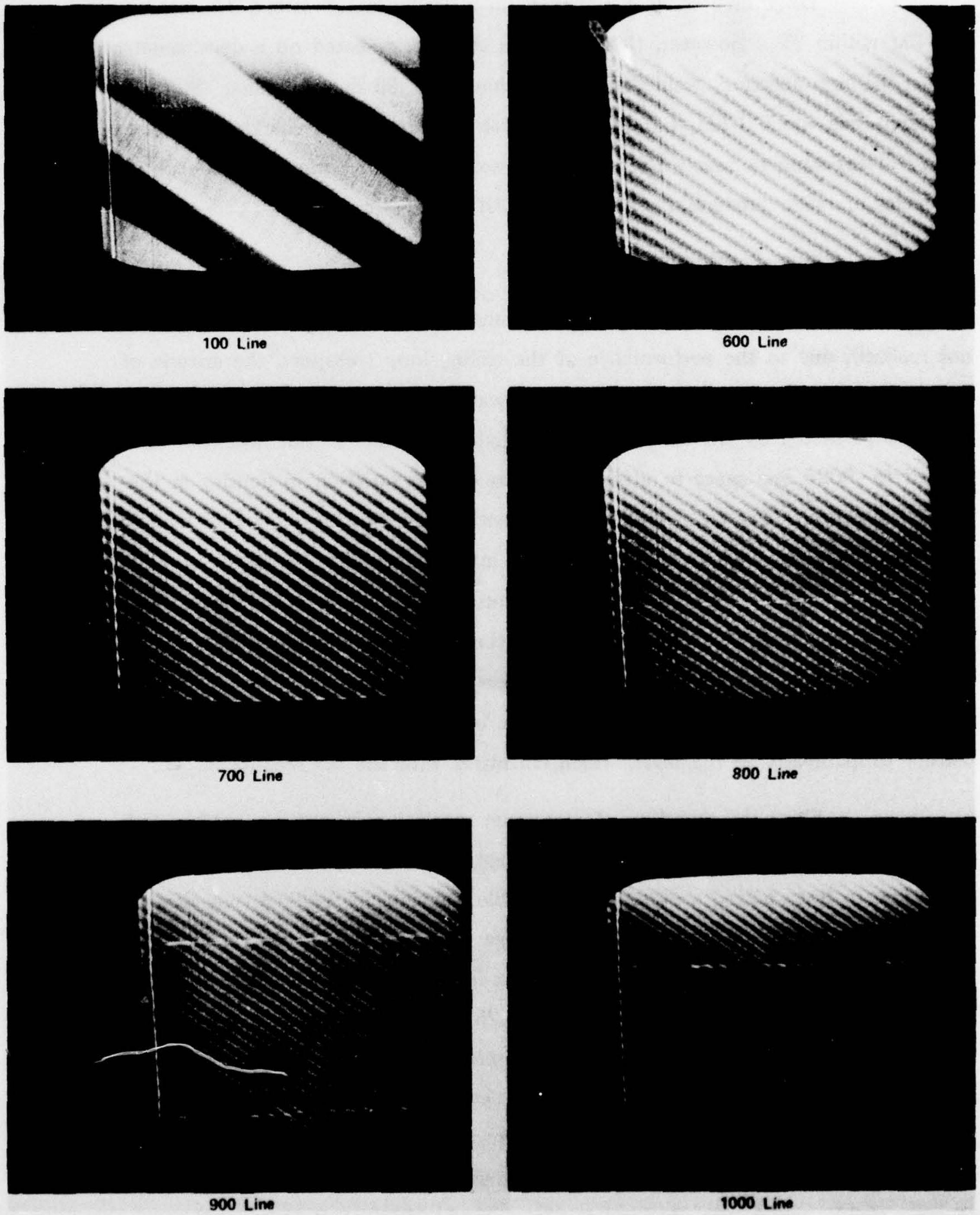


Figure 73 525 Line Cross Scan of 875 Line Per Frame Resolution. Pattern Throughput Electronics/Optics System

Large area shading, detected on a densitometer with a 2.5 mm aperture, was flat within 2%. However, the small area shading, detected on a densitometer with a 0.1 mm aperture, yielded a density change of .05 density units. Since the scan spot size was 5.3 μm, variation from peak to interstice in the raster ranged from full exposure to nearly fog level. The scan of the 0.1 mm aperture containing 20 cycles of raster predictably showed a $\triangle$D of .05.

4.3.2 Line Positioning and Spacing

Although full assessment of transfer of information to the film was not realized, due to the performance of the rolling loop transport, the criteria of apparent exposure level ripple due to raster scan (see Section 3.3.1) were not met. This was predicted by the analysis which indiated that line to line variation be limited to .0025 line space to attain a non-discernible variation in density in the vertical direction. The small-area density variation specification of ± .005 density units (S.O.W. para. 4.4.5.2) implies a line to interstice density difference of 20%, which is clearly perceptible, but requires a gaussian spot which is 3.45 times (at the e^{-2} intensity point) the line spacing. If the scan spot is astigmatized to a 3.5 to 1 ratio, vertical transfer function is decreased by approximately 60%. With the present spot configuration of approximately a one to one ratio, the interstitial density drops nearly to fog level, which correlates with the $\triangle$D reading of .05.

Since the retention of maximum resolution is not compatible with smoothing the raster effect, the most significant parameter in a raster scan appears to be line to line spacing accuracy. Discernible bunching or vertical (one dimensional) moire is detectible with a transmittance change of approximately 2%; at D = 1.0, this amounts to, with the film gamma of 3, a line space error of .16%. Frame to frame repeatability of the vertical scanner is .25%, reasonably close to the desired figure. However, the horizontal scanner pyramidal error of 10 arc seconds total, with 4.5 sec. line to line maximum, contributes a cyclic maximum line space error of .14 line space which, when observed directly at the image plane by eye, is barely perceptible. However, the amplifying effect of high gamma film makes this magnitude of error visible, which was observed in film records, although it is impossible to assign how much of the bunching was due to film slip and how much to polygon pyramidal error.

As discussed in Sections 3.1.3.6 and 3.9, a polygon error correction system utilizing the acousto-optic intensity control as a beam deflector corrected the polygon error to 1 arc second, which would bring the total line space error effect to a tolerable level. However, as previously discussed, the effect of the beam deflection on the modulators corrected the deflection error, but introduced a cyclic vignettting of the scan beam to an intolerable degree. The polygon error corrector is clearly feasible and necessary, but must be placed in the optical train after the acousto-optic modulators.

4.3.3 Critique of Film Records

Critical examination of the film records predominantly reveals the characteristics of the transport.

Figure 74 illustrates a typical frame of video recorded on film. The resolution test pattern of the 525 line per frame scan can be read in some areas into the 900 line area. This implies a limiting horizontal resolution at 525 line rate of 600 cycles per line. *However, the effects of slippage, strain release,* and misregistration are the most noticeable features of the recording. The effect of a continuing slippage as well as periodic perturbations are visible in the vertical moire or twinning artifacts. The light banding toward the bottom of the frame corresponds not to horizontal scanner periodicity, but to the periodicity of the transport rotor rollers encountering perforations in the film feed track. Apparently, the change in force in the passage of the perforation in the loop past the rollers produces sufficient thrust change in the film feed to deflect the film on the registration pin. The breakup at the top of the frame shows a slight lateral movement as film is first transferred in the loop at the gate.

Similar characteristics related to transport problems appear in Figure 75. The limiting resolution in this frame of 875 line video is 800 lines, or 530 cycles per line. The breakup appearing between the resolution pattern groups was an oscillation generated by the signal test generator. The vertical moire and banding in Figure 74 persists in this frame also.

The 875 line crosshatch pattern of Figure 76 shows the effect of a misregistration of approximately .007", which is the extreme beyond which the transport could be expected to jam. The upper portion of the frame shows the effect of a .002" slip until movement at about the 40% point of the frame or 20% of the first field was reached. At the top of the frame, the horizontal misregistration is observed. The progressively larger separation and breakup of the vertical lines indicate that the outer edge of the film departed from the focal plane. The vertical breakup is the characteristic of the dual pupil scan optic system; the depth of focus of the final focus lens is a function of line start criteria or time-position coincidence in the film plane, of the alternately scanning beams, rather than the depth of focus of the individual beams. Since alternate beams approach the film at different angles, displacement of the film from the point at which coincidence is registered produces the alternate line pair breakup.

Figure 77 is a film record of an iconoscope test pattern, directly comparable to Figure 70.

Figures 78 and 79 show film records of commercial 525 line TV. While misregistration is small (approaching .002") the twinning and discontinuity, or jump, at the 40% frame point is visible in each. Vertical banding structure is identified as the 3.58 MHz color carrier in the video.

Figure 80 shows the full format of the side by side Super-8 mm frames with their associated sound tracks.

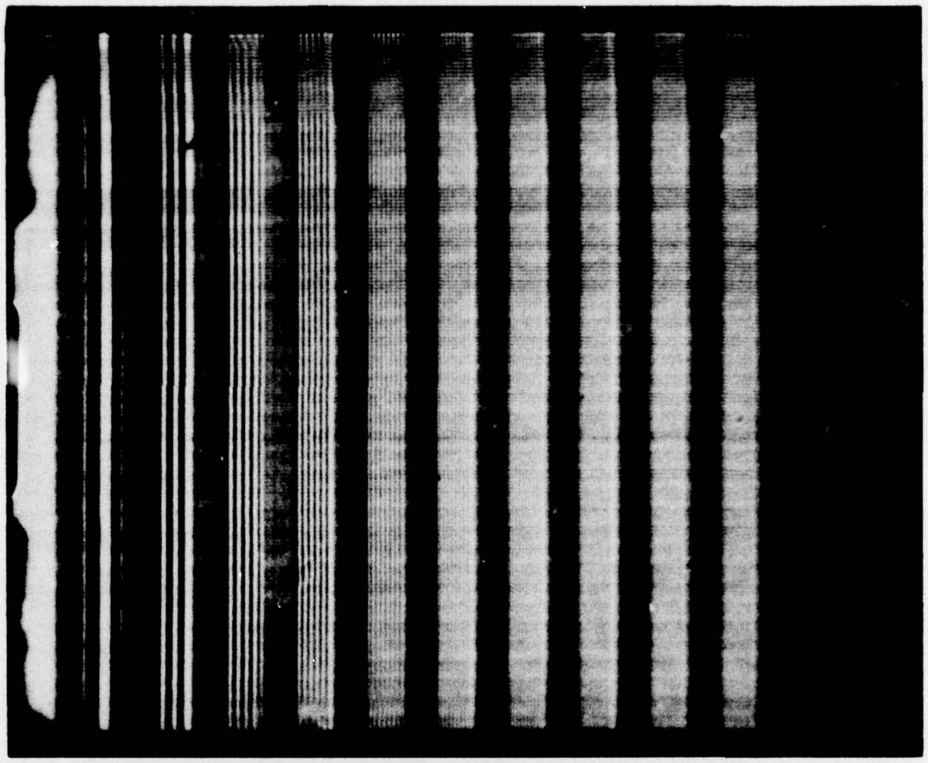


Figure 74 525 Line Multiburst Test Pattern

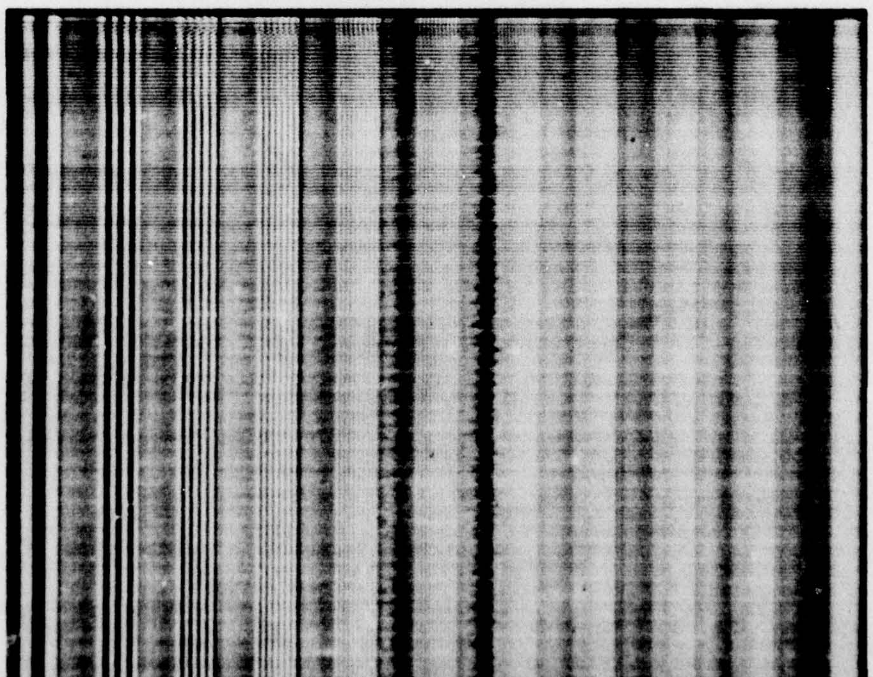


Figure 75 875 Line Multiburst Test Pattern

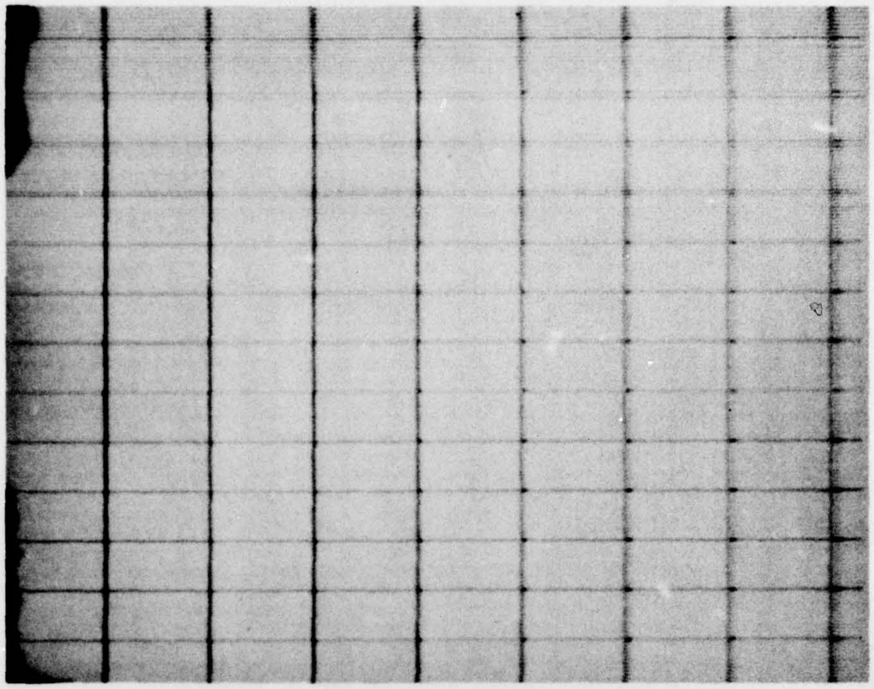


Figure 76 875 Line Cross Hatch Pattern

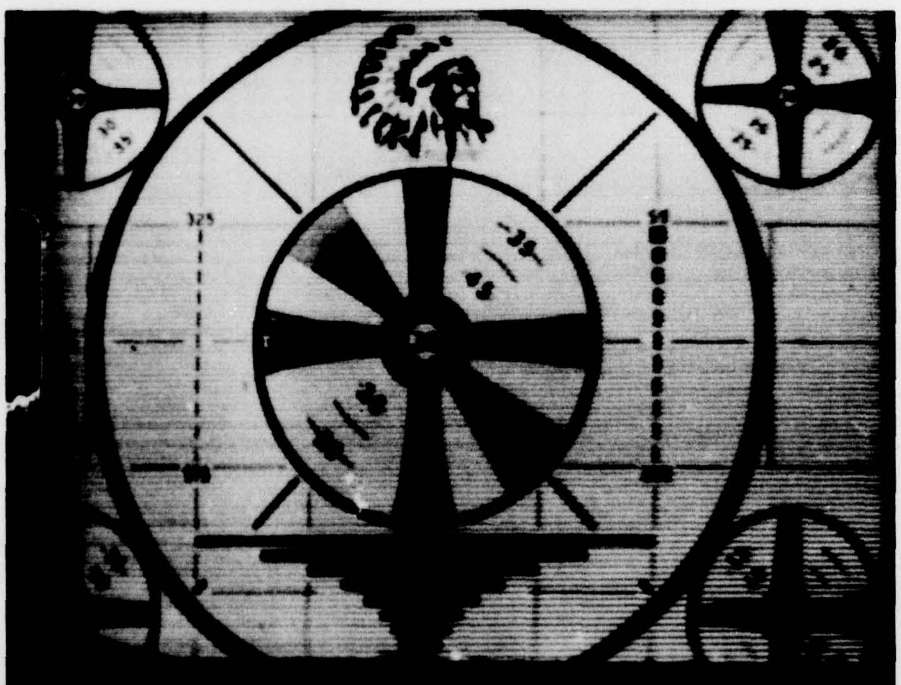


Figure 77 525 Line Konoscope Test Pattern

Figure 78 Commercial TV Recording

Figure 79 Commercial TV Recording

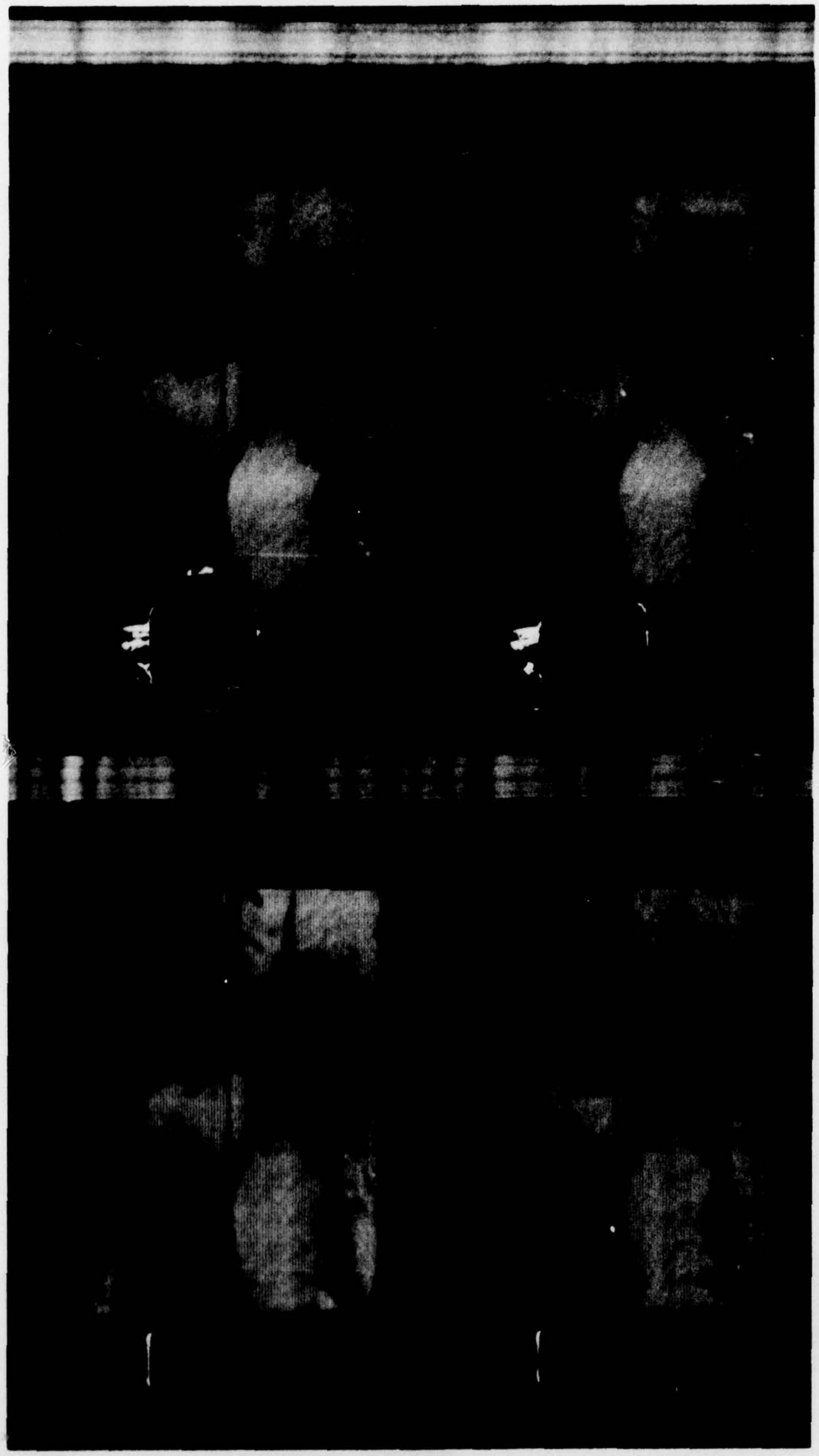


Figure 80 Full Film Format with Soundtrack

SECTION V
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

5.1.1 Laser Raster Scanning

The electronics/optical system of the laser recorder demonstrated full realization of bandwidth and resolution expectations. The accurate scanning and manipulation of the diffraction limited spot, unvignetted over the full field, with full modulation to 16 MHz shows the system to have an extremely high data transfer efficiency. As such, the laser raster scan system must be considered to have application where conservation of collected information and data is of prime importance.

5.1.2 Interlaced Video Format

The use of interlaced video format, essential to satisfactory display CRT viewing, is inimical to pictorial recording. The use of interlace requires a physical and temporal precision in the presently configured VLBR which which could be reduced by a factor of five, conservatively, if the video were sequentially line scanned. Typically, in the vertical scanner, line to line repeatability, point for point in the raster, must be under .01% to avoid noticeable twinning and image degradation in an interlaced system. In a non-interlaced format, a 0.1% repeatability would be adequate, with overall linearity of 1% sufficing. A 1% linearity in a non-interlaced picture would produce a pictorial distortion of 1/2%, probably less than the distortion introduced by the sensor system. By similar criteria, time base errors in the horizontal scan system become modest distortions instead of serious losses of resolution. While interlace complicates the high resolution raster scan system, it devastates a high resolution television rate film recording on any film transport yet devised.

5.1.3 Film Transport

With the high resolution interlaced video raster picture, the rolling loop transport, in principle and in practice, is inadequate to hold the film stationary during recording. The mechanism does not sufficiently isolate the film in the recording area from the loop feed, loop producing, and loop discharge forces to attain the stability required. However, with the thin base film and dual channel format of the VLBR, it is doubtful that any known film transport mechanism can attain a film movement of under 0.5 μm necessary to produce clean pictures from an interlaced video raster.

While the rolling loop mechanism is the most likely to attain pulldown times approaching video vertical blanking time, it must be considered as, at best, marginal among other mechanisms in other critical aspects.

5.1.4 Package

While the size and weight of the VLBR as configured exceeded the design goal of 3 cubic feet and 120 lbs., the use of avionics electronics and packaging techniques, combined with the design of a film transport to reduce weight, would appear to bring the package within limits.

5.2 Recommendations

5.2.1 Short Term Recommendations

The principal contributor to image degeneration was observed to be the film transport. To increase the utility level of the VLBR as delivered, it is recommended that the rolling loop transport be replaced with a conventional intermittent pulldown mechanism transport modified to take 16 mm film with a .1667" perforation pitch. In most well constructed transports, a four to six millisecond period to stabilize film appears feasible. As a specfic example, a modified Palmer double Super-8 camera will probably yield a 70 to 80% frame of image of considerably improved resolution. A Photosonics or Teledyne-Milliken high speed intermittent camera may also be considered as a suitable transport to yield similar performance.

However, it is unlikely that any mechanism presently extant can achieve better than $2\mu m$ stability during recording, which, in a 2:1 interlaced video raster with $5.3\ \mu m$ line spacing will seriously degrade the scanned image. Some gain in picture appearance, at the expense of information content, may be attained by elongating the scan spot in the vertical direction.

5.2.2 Long Term Recommendation

To attain the fullest utilization of the high resolution, wideband data transfer capability of the laser scanning system, the interlaced video data must be de-interlaced. With present and emerging technology, a high rate (75 MHz) A/D converter, a three field digital frame store, and D/A converter system, the bandwidth of 16 to 20 MHz can be maintained.

Such a system becomes predominantly electronic, and somewhat less mechanically complex. With the resulting sequential line scan, the film transport can be a continuous motion, tape transport type in which $.15\ \mu m$ line to line error is within the state of the art, and $0.10\ \mu m$ is possible. Vertical distortion of such a system can be under .25%. The vertical scanner is eliminated, and the horizontal scanner pyramidal error corrected acousto-optically. No information is lost between frames. The cost of the scan optics is reduced somewhat.

The system then stands to realize the very high data transfer efficiency possible from sensor to film.

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